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TRANSFORMER
PRINCIPLES AND PRACTICE

BY

J. B. GIBBS
Bachelor of Science in Electrical Engineering; Member of the American Institute of Electrical Engineers, Design Engineer, Westinghouse Electric Corporation

SECOND EDITION

McGRAW-HILL BOOK COMPANY, INC.
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1950

TRANSFORMER PRINCIPLES AND PRACTICE

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PREFACE TO THE SECOND EDITION

The kind reception which has been given this book indicates that it has met a need, and a new edition is desirable to bring the information up to date. The principles underlying transformer operation, of course, do not change; but our understanding of those principles improves, and the ways of applying the principles change as advances are made.

In this edition many examples of current practice are shown, and a new chapter on current-limiting reactors has been added.

Where the American Standards are mentioned, reference is made to the "American Standards for Transformers, Regulators, and Reactors," edition of 1948, published by the American Standards Association, New York. These Standards are generally accepted and followed in this country and to a considerable extent in other countries.

The author's thanks are again due the Westinghouse Electric Corporation for illustrations of typical designs. Thanks are due also to the American Standards Association for permission to quote parts of the American Standards.

J. B. Gibbs

Sharon, Pa.
July, 1949

PREFACE TO THE FIRST EDITION

A number of good books on transformers are available for the designer and for the student whose interest is largely in the theoretical and mathematical aspects of the subject. Many men in the electrical industry, however, would be glad of a nonmathematical description of some of the types of transformers and the principles underlying their operation. To such men it is hoped that this volume will prove useful.

In the body of the book, mathematical work has been limited to a few simple examples to illustrate the use of formulas which are given. For the benefit of those who care to go more deeply into the subject, Chapter XXIV has been included to show a method of solving transformer problems.

The foundation of this book is a number of articles which have appeared in the technical press, for the most part in *Power* and in the *Electric Journal*. These have been rewritten and brought up to date, and new material has been added. Much of the chapter on constant-current-regulating transformers is taken from an article on the same subject in the *Electric Journal*, and the chapters on transformer cooling and on old versus new transformers follow closely articles which were published in *Power*. The photographs used for illustration were supplied by the Westinghouse Electric and Manufacturing Company. They illustrate good modern practice as applied to the apparatus shown, but of course various constructions are used by various manufacturers.

As this is written, the question of transformer standards is somewhat unsettled. A committee of the American Standards Association has been at work for about two years on a revision and unification of the standard rules of the American Institute of Electrical Engineers, the National Electrical Manufacturers' Association, and the Edision Electric Institute. The committee has agreed on a report which will shortly be published, and it seems probable that this report will be adopted, possibly with minor modifications, as American Standards for Transformers.

The statements in this book as to standards refer to the committee report.

Thanks are due to *Power* and to the *Electric Journal* for permission to republish parts of articles and to the Westinghouse Electric and Manufacturing Company for the illustrations.

J. B. GIBBS

SHARON, PA.
September, 1937

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CHAPTER I

INTRODUCTION

When Michael Faraday announced the discovery of electromagnetic induction in 1831, he laid the foundation for the present electrical industry. Faraday found that a current of electricity flowing in a coil of wire around a piece of iron would convert the iron into a magnet and that, if this magnet were inserted into another coil of wire, a galvanometer connected to the terminals of the second coil would be deflected. This is the principle on which transformers operate, and it is hard to conceive of modern power systems without the convenience and economy that transformers make possible.

Historical. For many years after Faraday's announcement his discovery had no "practical value." Other experimenters repeated his experiments and went on to build induction coils operated with interrupted direct current to give shocks or sparks, but there was no thought of the transformer as a means for the economical distribution of power.

At length the idea did develop, and in 1882 patents were granted in England to Gaulard and Gibbs for a system of distributing power using alternating current and transformers. The transformers used were 1:1 ratio and were connected in series on the primary side. The result, of course, was unsatisfactory regulation unless all the transformers were equally loaded, and the system was not a success, but the principle of power transformation was established.

These patents came to the attention of George Westinghouse, and in 1885 he acquired the American rights under the patents and selected William Stanley to develop the transformer. Stanley worked out a practical form and applied, although he probably did not originate, the idea of connecting the transformers in parallel. In 1886 he succeeded in lighting some stores in Great Barrington, Mass., at a distance of about half a mile from the generator, using 500 volts on the line and transformers to step down the voltage at the receiving end. The success of this installation led to the establishment of other alternating-current systems.

For several years there was much heated opposition to the "deadly alternating current," with its high voltages, and legislation was sought to prohibit it. But the economic advantages were so evident that it became the accepted system of distribution, and with the rise of the alternating-current system arose the need for transformers.

Function of the Transformer. The function of the transformer is to change electric power from one voltage to another. The voltage at which power is used depends on the purpose to which it is to be applied. For lighting, household devices, and small motors, 120 volts is generally used. Larger motors are fed at 240 volts or 480 volts, and still larger motors at higher voltages. But any considerable amount of power transmitted even a few miles at such voltages would take an enormous amount of copper in the lines and make the cost of electric service prohibitive.

Power in an alternating-current circuit depends on the voltage between lines, the current flowing in the lines, and the *power factor*. For a given amount of power, therefore, the higher the voltage the lower the current, and the lower the current the smaller the wires which can be used to transmit it. The use of transformers enables power to be generated at any convenient voltage, stepped up to an economical transmission voltage, and stepped down again at the end of the transmission line to the desired voltage for use.

For instance, at Hoover Dam, power is generated at 13,800 volts. This is stepped up by means of transformers to 287,000 volts for transmission to Los Angeles, a distance of 273 miles. At the receiving end of the line the voltage is stepped down to 132,000 volts for delivery to five main receiving stations. Here it is stepped down again, this time to 34,500 volts, for distribution around the district. The 34,500-volt lines feed distribution substations where the voltage is reduced to 4,600 volts for local distribution. And the 4,600-volt lines feed the transformers which make the final reduction in voltage to the 240–120 volts required by most customers. Figure 1 is a schematic diagram of the system. The power passes through five sets of transformers after it leaves the generators and before it reaches the consumer, and the total loss in the transformers is something like 5 per cent, at rated load. A good transformer is a very efficient piece of apparatus.

Characteristics of Transformers. Transformers apply Faraday's discovery by using two copper circuits linked with an iron circuit. The iron circuit is built up of thin plates of special steel. The two copper circuits may be entirely independent and insulated from each other, as in two-winding transformers, or they may have part of their turns in common, as in an autotransformer. When an alternating voltage is applied to the terminals of one of the copper circuits, an alternating current will flow which will magnetize the core first in one direction and then in the other. This induces a voltage in the second coil, and if lamps or other loads are connected to the terminals of the second coil, current will flow. The ratio of the primary to the secondary volts is the same as the ratio of primary to secondary turns, and the ratio of the primary to the secondary amperes is the same as the ratio of secondary to primary turns.

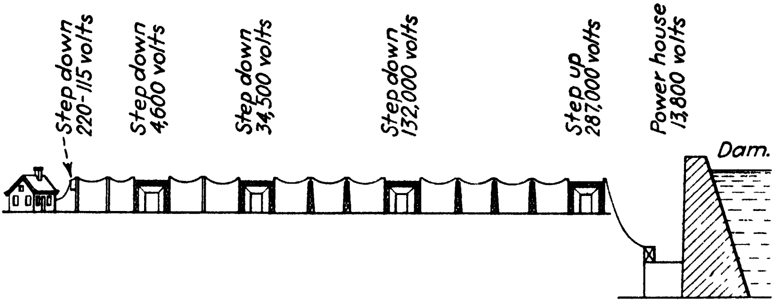

FIG. 1. Schematic view of power transmission, Hoover Dam to Los Angeles.

Design Problems. When current flows in a transformer, heat is generated, both in the coils and in the core. Too much heat, however, is an enemy of insulation, and one of the designer's major problems is to prevent the transformer from reaching too high a temperature. Other major problems are to provide sufficient insulation and to arrange it so that the transformer will withstand any voltage condition which it may encounter in operation, to produce a transformer which will operate with satisfactorily low losses, and to keep the material used, and consequently the cost, at a minimum.

This array of requirements calls for the exercise of skill and ingenuity on the part of the designer, and in the effort to get the best solution many and various arrangements of cores and coils have been worked out. Each arrangement has certain advantages, and several typical schemes will be shown. All the arrangements fall within one or the other of two general classes, called, respectively, *shell form* and *core form.*

Mechanical Forms. The shell-form construction is shown schematically in Fig. 2. The coils are more or less rectangular in shape, and the iron is built through the opening and around the outside of the coils to form a shell around the straight part. Each lamination of the iron, when assembled, forms a rectangle with two *windows* through which the coils pass.

In the core-form transformer, illustrated in Fig. 3, the iron is in the shape of two cores, or *legs*, surrounded by the coils and joined at the ends by *yokes*. The word *core* is also used to include all the iron in the magnetic circuit.

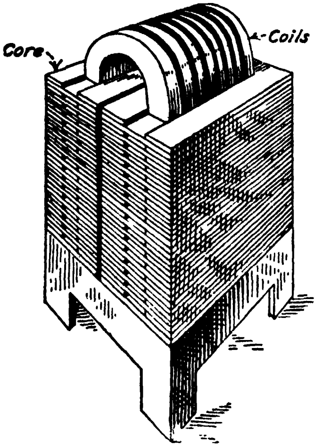

FIG. 2. Shell-form transformer.

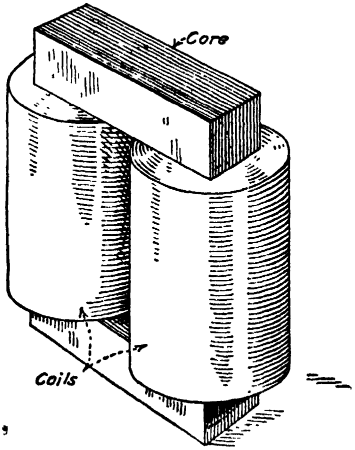

FIG. 3. Core-form transformer.

Cooling Methods. Transformers may also be classified with regard to their method of cooling. *Dry-type* transformers are designed for operation without oil. Small dry-type transformers may be mounted in end frames with the coils exposed, for indoor operation, or they may be provided with metal housings for protection Such transformers are cooled by the natural circulation of air around their coils and core. In large and medium-sized dry-type transformers additional cooling is provided by air ducts through the winding. And in *air-blast* power transformers the winding and the core are provided with many ducts through which air is forced at high speed by a blower.

With the exception of the transformers just mentioned and of some instrument transformers which will be described later, it is the general practice to use *oil-immersed* transformers. The coils and core are mounted in a tank filled with oil, which serves the double purpose of helping to insulate the transformer and of carrying the heat caused by the transformer losses to the cooling surfaces where it is dissipated.

In certain locations oil is prohibited on account of fire hazard. If a dry-type or an air-blast transformer is not suitable, an askarel-filled* transformer may be used. Under normal conditions askarel requires about the same care in handling as oil.

The use of oil or askarel calls for a container which will hold the liquid and the transformer and protect them from dirt and moisture and at the same time permit the dissipation of heat. It is also necessary to get leads from the transformer out of the container and to insulate them suitably. These various features will be discussed more fully in later chapters.

Field of Transformers. The field of transformers is very broad, for probably 99 per cent of all the electrical energy generated passes through one or more transformers. Much even of the direct-current power which is used on some electric railways and in certain electrochemical processes is generated as alternating-current power and converted to direct current by rotary converters, motor generators, or rectifiers. Transformers are required in connection with all these devices.

In size, transformers range from bell ringers and small radio transformers, which can easily be held in one hand, to power transformers, which may require a floor space of 25 by 40 feet and may have a height over the bushings of 32 feet. In output they range from a few watts to 125,000 kva or more in a single unit.

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* Askarel is a name adopted by the American Standards Association to apply to noncombustible synthetic insulating liquids which do not give off explosive gases when decomposed by an electric arc. The same or similar askarel is sold by different companies under their own trade names.

CHAPTER II

SINGLE-PHASE AND THREE-PHASE TRANSFORMERS

Practically all transformers are either single-phase transformers or three-phase transformers. Most transmission lines are three-phase, and these can be served either by three-phase transformers or by banks of single-phase transformers. Other multiphase circuits are sometimes required, *e.g.*, two-phase for certain motors, six-phase for most rotary converters, and twelve or more phases for large rectifiers, but they can all be derived from three-phase circuits by means of transformers.

Transformer Theory. The fundamental fact about a transformer is that energy can be transferred from one winding to another winding on the same magnetic circuit by means of a varying magnetic flux. The winding which receives energy from an external source is called the *primary* winding, and that which receives energy from the primary by magnetic induction is called the *secondary* winding. A transformer may have one or more secondary windings.

When an alternating voltage is impressed on the primary winding, a small current will flow. This is the exciting current which produces the magnetic flux in the magnetic circuit. This flux, linking the turns of the primary winding, induces a voltage practically equal and opposite to the applied voltage.* And the same flux, linking the turns of the secondary winding, induces the same volts per turn as in the primary. The ratio of primary to secondary volts, therefore, is the same as the ratio of primary to secondary turns.

If a load is connected to the secondary winding, the induced secondary voltage will cause a current to flow. The ampere turns thus produced in the secondary winding must be balanced by equal and opposite ampere turns in the primary winding. The ratio of secondary-load amperes to primary-load amperes, therefore, is the same as the ratio of primary turns to secondary turns. From these relations of primary to secondary volts and amperes it follows that the primary kilovolt-ampere input is the same, neglecting losses, as the secondary kilovolt-ampere output.

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* There is actually a small difference on account of the voltage drop necessary to overcome the impedance of the primary winding, but this difference is usually negligible.

Any desired voltage may be obtained by means of a transformer of the proper ratio from any available voltage of the same frequency.

Single-phase Transformers. The usual single-phase transformer has one primary winding, to which power is fed, and one secondary winding, which takes power by induction from the primary winding and supplies power to a load. A few transformers are provided also with a tertiary winding, which may be used to supply power at a different voltage from that of the secondary winding or may be used in connection with certain combinations of transformers in three-phase banks. This latter application will be discussed later. Single-phase transformers are made in all sizes and for all voltages and in both shell-form and core-form constructions. No rigid statement of the field of each of these forms can be made, but in general the shell form has certain advantages for transformers which require a fairly large cross section of copper, transformers of large output, or transformers for low voltage and heavy current. The core form, on the other hand, has advantages for transformers which take a small cross section of copper, such as small high-voltage transformers. Even these rules have many exceptions. Much depends on the preference of the designer and of the user.

Single-phase transformers are much used, even for three-phase transformation, by connecting them in banks of three transformers. In fact, the vast majority of large single-phase transformers is used on three-phase circuits.

THREE-PHASE TRANSFORMERS

In building transformers for three-phase circuits the three windings can be combined on a single iron core. This makes it possible to take advantage of the phase difference in the three circuits so as to save a part of the material.

Three-phase Core-form Transformers. Figure 4 represents three single-phase core-form transformers of the same size. The full lines indicate the cores, and the dotted lines the space occupied by the coils. Now suppose that the three cores are pushed together so that they touch, as in Fig. 5, and that the shaded portion of the iron is cut away. Also, take the unshaded strip at the right of *C* and transfer it to the left of *A*, as shown by the dotted lines in Fig. 5. This gives the iron circuit shown in Fig. 6, which has the same cross section of iron as each circuit in Fig. 4 and has also an increased space for coils, besides saving the portion of the iron shown shaded in Fig. 5. This is not all clear gain, however, for the total cross section of copper in the coils for Fig. 6 must be the same as for Fig. 4, while the mean turn will be greater because the coils are thicker. In practice, a part of the saving is taken out of the iron circuit and a part out of the copper circuit, and the net result is that the active material in a three-phase transformer costs about 10 per cent less than the active material in three equivalent single-phase transformers. The cost of the active material may be something like half that of the complete transformer, so the actual difference in cost between a three-phase transformer and a bank of three single-phase transformers may depend as much on the mechanical as on the electrical design.

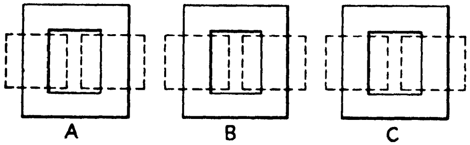


FIG. 4. Core form, three single-phase cores.

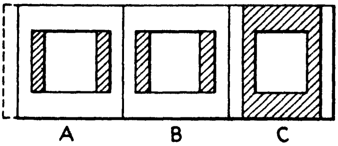


FIG. 5. Core form, iron saved by three-phase core.

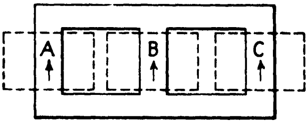


FIG. 6. Core form, three-phase core

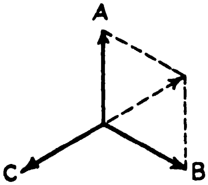


FIG. 7. Flux vectors in three-phase core-form core.

A vector diagram of the fluxes in the three legs of a three-phase core-form transformer is given in Fig. 7, which shows that the resultant of the fluxes in any two legs, as indicated by the dotted lines, is just equal and opposite to the flux in the third leg. This means that at any instant the sum of the *up* fluxes in any two legs is equal to the *down* flux in the third leg.

Three-phase Shell-form Transformers. In a similar way three single-phase shell-form cores can be combined to form a three-phase shell-form unit. Figures 8, 9, and 10 correspond, respectively, to Figs. 4, 5, and 6. Figure 8 shows the magnetic circuits of three single-phase shell-form transformers; Fig. 9, by the shaded part, indicates the iron which can be saved by the combination; and Fig. 10 represents a three-phase shell-form core. In this case the single-phase coils might be used without change, and the total saving would be represented by the shaded part of the iron in Fig. 9.

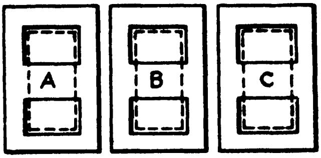


FIG. 8. Shell form, three single-phase cores.

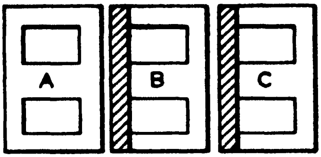


FIG. 9. Shell form, iron saved by three-phase core.

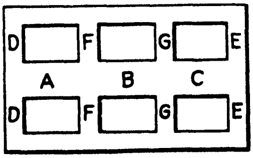


FIG. 10. Shell form, three-phase core.

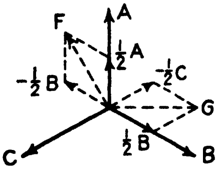


FIG. 11. Flux vectors in shell-form three-phase core with all coils similarly connected.

The magnetic flux in the parts of the core marked *D* and *E* (Fig. 10) will evidently be half of the flux in the cores *A* and *C*, respectively. Consider how much flux there will be in the other parts of the iron. Since the coils are connected in a three-phase circuit, the fluxes in the three cores must be 120 degrees apart, as shown by *A*, *B*, and *C* (Fig. 11). Suppose first that the coils are connected symmetrically in the three circuits. Then the flux in *F* will be the vector sum of half the flux in *A* minus half the flux in *B*. The construction is shown in Fig. 11 by the dotted lines, and the resultant is a flux in *F* which is 0.866 of the flux in *A* or in *B*. Similarly, the flux in *G* will be the vector sum of half the flux in *B* minus half the flux in *C*, or 0.866 of the flux in *B* or *C*. This would necessitate having the iron in the parts *F* and *G* 0.866 as wide as the iron in the cores *A*, *B*, and *C* and would result in very little saving of material. Now suppose that we reverse the connections of the coils on the core *B*, so that the direction of the flux is reversed with respect to the flux in *A* and *C*. The flux in *F* will now be the vector sum of half the flux in *A* plus half the flux in *B*. The construction for this is shown in Fig. 12, and the resultant is found to be equal to half the flux in *A* or *B*. Likewise, the flux in *G* is half the flux in *B* or *C*. In a shell-form three-phase transformer, therefore, the windings on the middle leg are always reversed, and the parts *D*, *E*, *F*, and *G* of the iron circuit are all made half as wide as the cores *A*, *B*, and *C*.

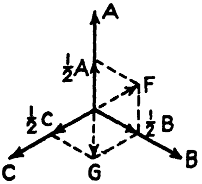


FIG. 12. Flux vectors in shell-form three-phase core with middle coil reversed.

Connection of Three-phase Transformers. It is the usual practice to make the connections between phases in a three-phase transformer at a terminal board below the oil level in the case. This makes it possible to bring only three high-voltage leads and three low-voltage leads out of the case and greatly simplifies connection to the lines.

Four principal ways of connecting the windings of three-phase transformers are in use: delta-delta, Y-delta, delta-Y, and Y-Y. These are discussed in the chapters on Transformer Polarity and Usual Transformer Connections.

In case of trouble in one phase of a three-phase transformer, the other two phases may be operated in open delta to carry 58 per cent of the rating, provided that the transformer is connected delta-delta. This is the same statement that can be made concerning a bank of single-phase transformers. To make this change in a three-phase transformer it is necessary to disconnect both high-voltage and low-voltage windings of the damaged phase at the terminal boards. If the transformer is of the core form, both windings of the damaged phase must be open circuited. If the transformer is of the shell form, the damaged windings may be open circuited or short circuited. The reason for this can be seen by considering the shape of the magnetic circuits. Suppose that the windings on core *B* are damaged in Figs. 6 and 10. If phases *A* and *C* are to run in open delta, it is necessary that the fluxes in these two cores be 120 degrees apart and that the resultant flux have a return path. In the core form (Fig. 6) this return path is provided by the third leg *B*. But if there is a winding on core *B*, the flux passing through it will induce a voltage, and if there is a closed circuit, a current will flow. This will increase to the point where the coil on *B* will be burned out. In the shell-form transformer (Fig. 10) the core *B* does not provide the only path for the return flux, and if the coil is short circuited, it merely causes the flux to take the other path.

Single-phase versus Three-phase Transformers. The choice between a three-phase transformer and a bank of single-phase transformers depends largely on the judgment of the engineer who is buying them, but in general, three-phase transformers are more popular than they were several years ago. This is due partly to improvements in design and insulation but principally to the better acquaintance of operating men with the three-phase type. The chief arguments for and against a three-phase transformer as compared with a bank of single-phase transformers may be summarized thus:

For:

1. Occupies less floor space.
2. Weighs less.
3. Costs less.
4. Only one unit to handle and connect.

Against·

1. Greater weight per unit.
2. The average line man is more familiar with single-phase transformers.
3. In three-phase transformers trouble in one phase may be communicated to other phases.

The last objection does not carry much weight. In shell-form three-phase transformers the separation of phases is almost as effective as in three single-phase transformers, while even in the core form, heavy insulating barriers are always put between the windings on different legs, so that breakdowns from this cause are rare.

CHAPTER III

COILS AND CORES

In the ideal transformer both the copper and the iron circuits would be so arranged that the total value of material would be a minimum. To fulfill this condition both circuits would have circular cross sections and circular mean turns. With such an arrangement the core-form transformer would be built as shown in Fig. 13. The core would be a torus ring of iron, and the coils would be wound through the opening in the core so as to fill the space inside the ring. The shell-form transformer would look like Fig. 14. The coils would form the torus ring at the center, and the iron would be arranged to surround the coils and fill the space inside the ring. Actually neither of these forms is practicable because of difficulties of construction and insulation. Practical coils take a form which can be wound on a mold in a winding lathe instead of being drawn through the core by hand, and practical cores

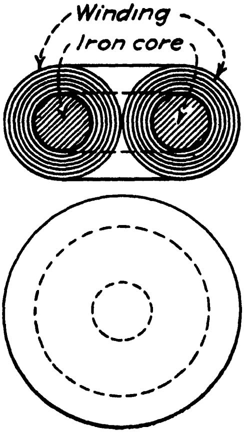


FIG. 13. Ideal core-form transformer.

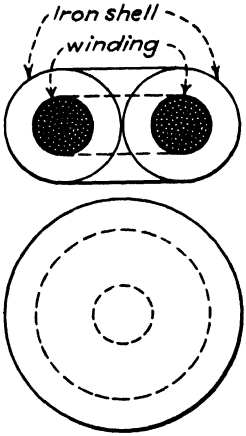


FIG. 14. Ideal shell-form transformer.

are built up of thin sheets of magnetic material. These ideal forms, however, have guided the thought of designers, and the various actual transformers approach one or the other of these forms more or less closely.

COILS

Transformer coils are designed to get the required number of turns into a minimum of space. At the same time the cross section of the conductor must be large enough to carry the current without overheating, and room enough must be provided for insulation and for cooling ducts. Transformer coils are always made of copper because it has the lowest resistance of any of the cheap metals. Aluminum has been proposed for this use, but for the same resistance it requires a larger cross section than copper and, consequently, a larger opening in the iron.

For coils which are to carry small currents, round copper wire is used. It may be insulated with cotton, insulating enamel, paper, or a combination of these materials. The object is to get the required insulation strength with a minimum thickness. For transformers, round wire larger than number 10 is rarely used because of the waste space between wires. If large cross sections are needed, either square wire or rectangular copper ribbon is used, insulated with cotton or preferably with paper. Transformers intended for operation at high temperatures use copper insulated with glass or asbestos.

I^2R Loss. The cross section of the copper conductor depends on the current to be carried and on the permissible energy loss. The loss is caused by the current flowing through the resistance of the copper and is computed by multiplying the resistance by the square of the current. It appears as heat in the coil, and it may be necessary to limit this loss either to prevent overheating or to meet efficiency guarantees.

Eddy-current Loss. If a conductor is placed in an alternating magnetic field, eddy currents are set up in the body of the conductor which increase the effective resistance of the conductor and consequently increase the copper loss. The amount of the increase depends on the size of the conductor, the strength of the magnetic field, and the frequency. In round wire coils and coils made of small strap the increase is negligible at usual frequencies. In coils to carry heavy currents, which require a large cross section of copper, the eddy current is minimized by building up the required cross section from a number of small insulated conductors in parallel. These are transposed at intervals; *i.e.*, they are twisted so that each conductor in the course of its length occupies various positions in the group. In each small conductor this cuts down the voltage which sets up eddy currents, and thus it decreases the heating and improves the efficiency.

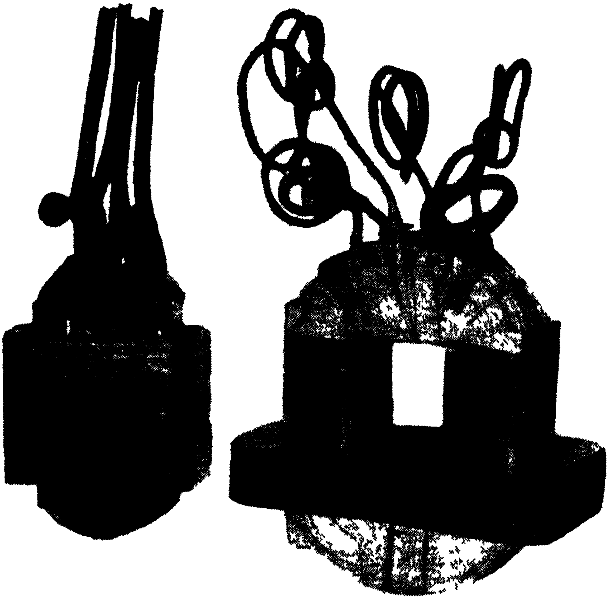


FIG. 15. Small dry-type transformer partly built.

Dry-type Coils. The type of coil into which the conductor is wound depends on the requirements as to insulation and cooling. Small dry-type transformers rely on the natural circulation of air around their coils and core to keep them cool. Such transformers are made for voltages up to about 480 volts, and for the smaller sizes—up to about 10 kva—the high-voltage coil may be wound directly over the insulated low-voltage coil, either on the insulated iron core or on a separate mold. Figure 15 shows such a coil.

Dry-type transformers above 10 kva need additional cooling surface in order to get rid of their heat. This increased surface is provided by placing ducts so as to permit the circulation of air between the coils as well as around the outside. Such transformers may be wound with flat, or *pancake*, coils and assembled with spacers between the coils to form the ducts, or the coils may be arranged one inside the other with ducts between. Figure 16 is an example of the pancake construction, and Fig. 17 of concentric coils. Such coils are used for transformers up to about 200 kva.

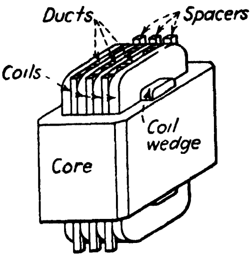


FIG. 16. Ducts between pancake coils.

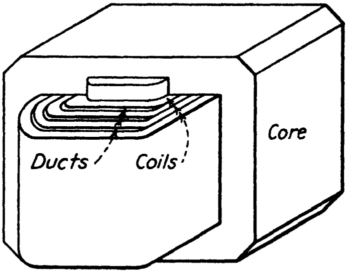


FIG. 17. Ducts between concentric coils.

Coils for still larger dry-type transformers have been built as shown in Fig. 18. In this construction the core form is used. The iron core is surrounded by a cylinder of insulating material. Outside this the low-voltage coil is wound in thin layers separated by spacers so as to form vertical ducts. Another heavy insulating cylinder and additional air ducts separate the low-voltage winding from the high-voltage winding, which usually consists of a number of flat circular pancake coils stacked one above the other. Spacers are placed between the coils and between the insulating cylinder and the stack of coils. This makes an open construction through which air can circulate freely.

Air-blast Transformer Coils. Air-blast transformers are usually shell form and use pancake coils. Ducts are located so that one side of each conductor is exposed to the cooling air, which is forced through the ducts by a blower. This ensures a uniform low temperature throughout the transformer.

Oil-immersed Transformer Coils. Coils for oil-immersed transformers assume a variety of forms, depending on the size and type of the transformer in which they are to be used. For small oil-insulated distribution transformers with rectangular cores, the coils are wound on rectangular molds or on the insulated core. Figure 19 shows such a coil in process of winding.

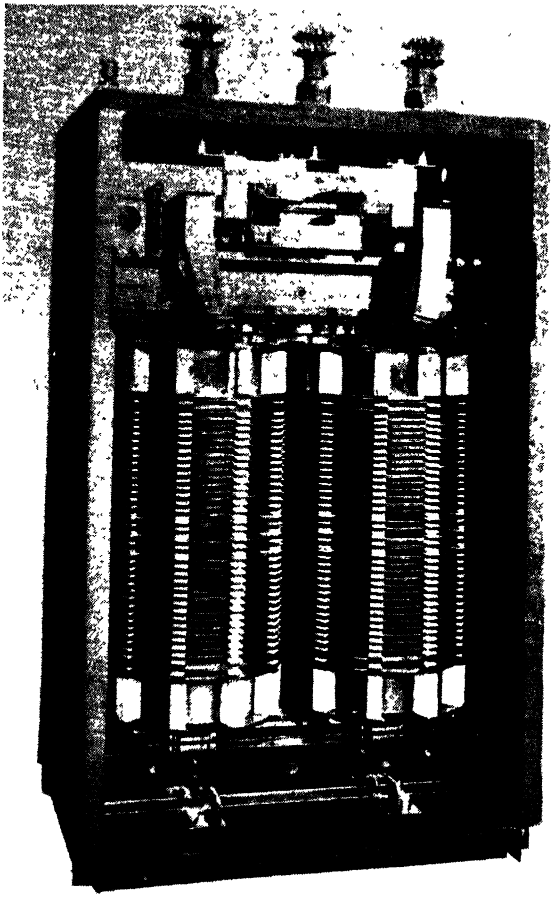


FIG. 18. Self-cooled dry-type transformer with case removed.

For transformers of the smallest sizes the low-voltage coil is usually wound first, and the high-voltage coil is wound over an insulating layer around the low-voltage coil. Or the high-voltage coil may be wound on a mold of its own and separated from the low-voltage coil by an insulating tube.

For transformers of somewhat larger size the low-voltage wind-

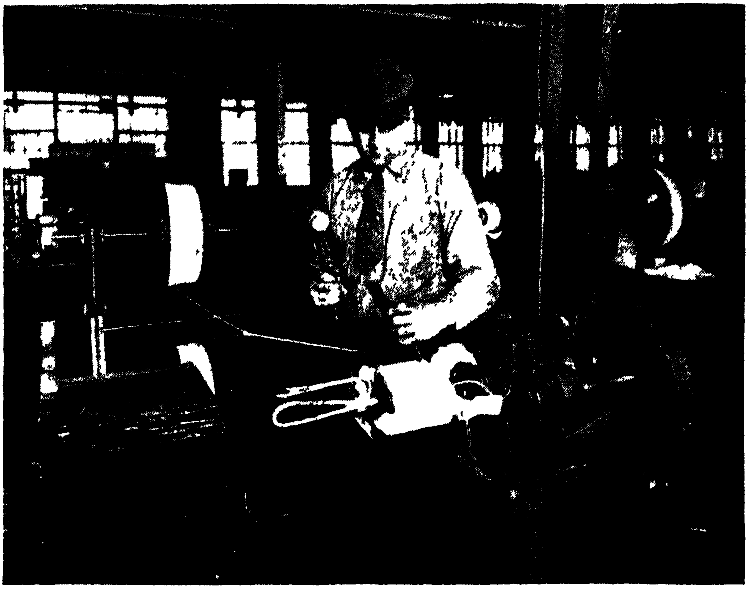


FIG 19. Winding a low-voltage coil for a small oil-insulated transformer.

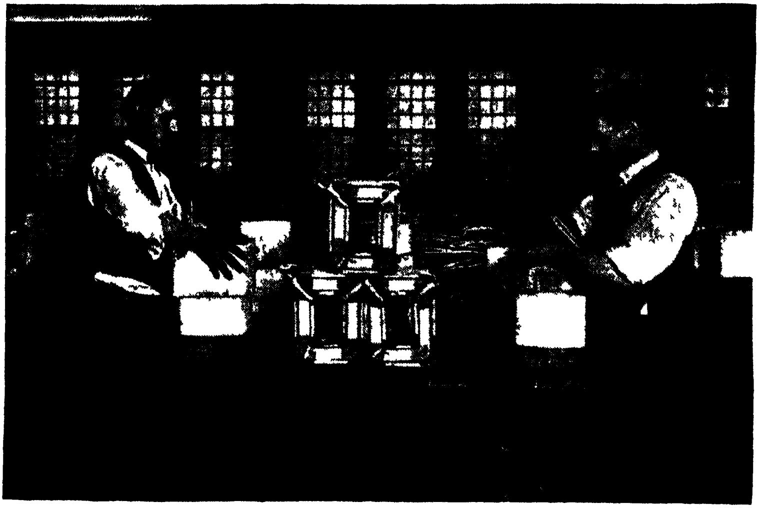


FIG. 20. Assembling coils for small oil-insulated transformers.

ing is divided into two parts, one inside the high-voltage coil and one outside. In this case oil ducts are provided between the coils, either at the corners or at the ends of the coils. Figure 20 shows an assembly of coils of this type. In the coils piled on the bench the connections between the two parts of the low-voltage winding can be seen at the upper corners of the coils and the high-voltage connections at the lower corners. The oil ducts can also be seen at the corners between the coils.

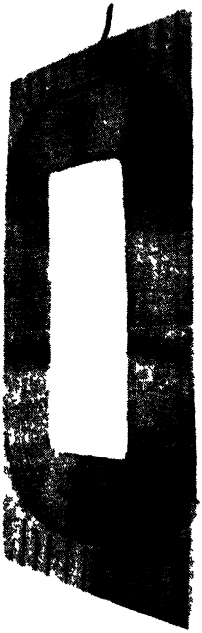


Fig 21 Pancake coil for shell-form transformer

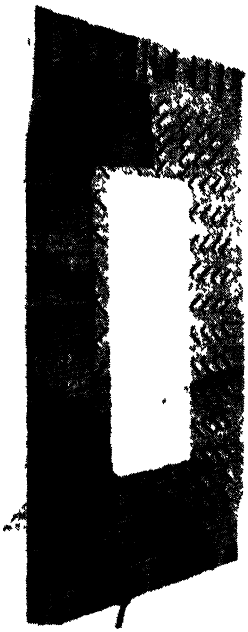


Fig 22 Pancake coil cut away to show insulating washer and spacer blocks

The coils of small oil-insulated transformers are generally dried in vacuum and then impregnated with a special varnish. This improves the insulation, strengthens the coils mechanically, and improves the ability to get rid of heat. Coils for askarel-filled transformers are treated with shellac or similar material because most of the insulating varnishes are soluble in askarel.

Coils for Large Transformers. In large transformers satisfactory cooling is more difficult, and an effort is made to bring the oil into contact with each wire in the coils. A considerable part of the space in the iron opening is taken up with oil ducts. Coils for large shell-form transformers are wound in pancake shape, often with the width of copper ribbon equal to the thickness of the pancake. The wire is wound with one turn per layer, like a clockspring. Figure 21 shows such a coil. Two of these coils are often assembled together with their start leads connected and with an insulating washer between the coils. This forms a two-section coil with both leads on the outside.

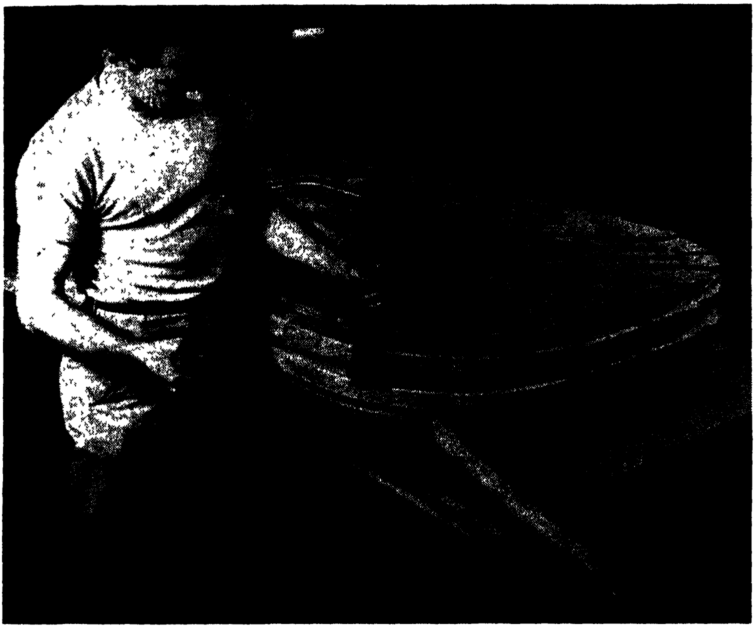


FIG. 23. Group of coils for large shell-form transformer, with insulation.

Section-wound coils are assembled with insulating washers and spacers between them, so as to allow free passage of the cooling oil along at least one face of each section. The spacers are made so that no one conductor in the coil will be completely blanketed and yet so that each conductor will be supported at short distances along its length. One way of accomplishing this is to glue small pressboard blocks to the washer which separates the coils.

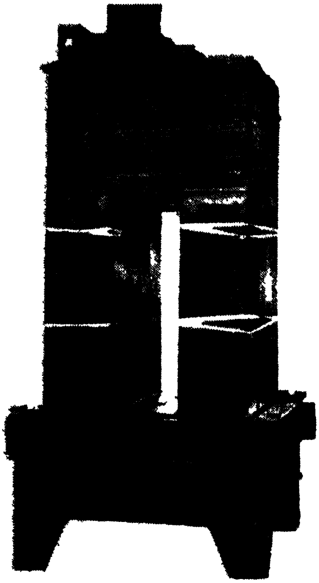


Fig 24 Completely assembled coils for large shell form transformer with lower end frame

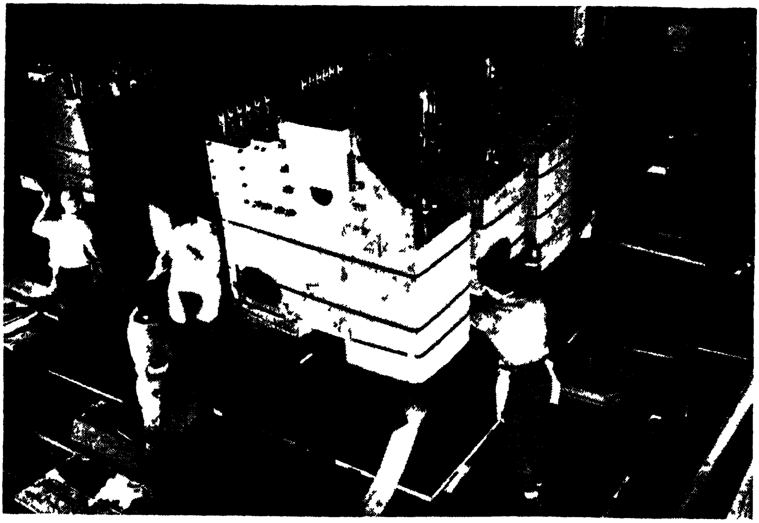


Fig. 25. Building punchings into coils—large shell-form transformer.

Figure 22 shows a pancake coil cut away so as to show the insulating washer and the spacing blocks. This allows the oil to circulate freely and cool each wire in the coil.

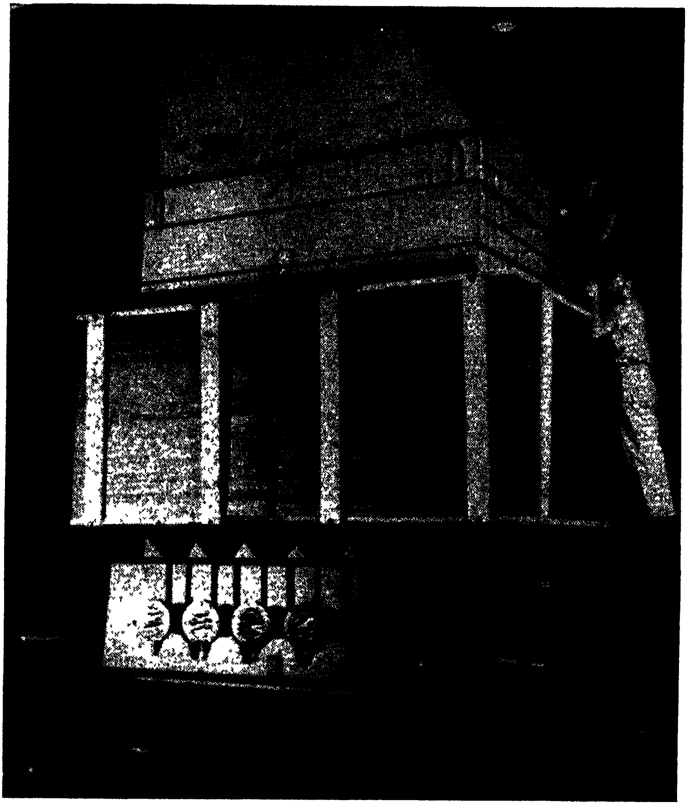


Fig. 26. Completely assembled coils and core for large shell-form transformer.

The individual coils with their separating washers are assembled into high-voltage groups and low-voltage groups, and these groups, in turn, are assembled with suitable insulation to form the complete transformer winding. Figure 23 is an end view of a partly assembled set of coils, and Fig. 24 shows a completely assembled set of coils ready for the core. Figure 25 shows the process of building the core around the coils, and Fig. 26 is a view of completely assembled coils and core.

Coils for large core-form transformers are usually made circular or cylindrical in shape. Here, as in the smaller transformers, the coils are sometimes wound one over the other on a single mold. More often they are wound on separate molds, after which they are assembled with insulating barriers between them. The ideal arrangement in core-form as in shell-form transformers is to have oil flow freely against one side of each conductor, but this cannot always be accomplished. For instance, in coils made of a large number of turns of fine wire it is necessary to wind several turns per layer, but the coils are made small enough in cross section so that there is no danger of overheating, and a large part of the surface is exposed to the cooling oil.

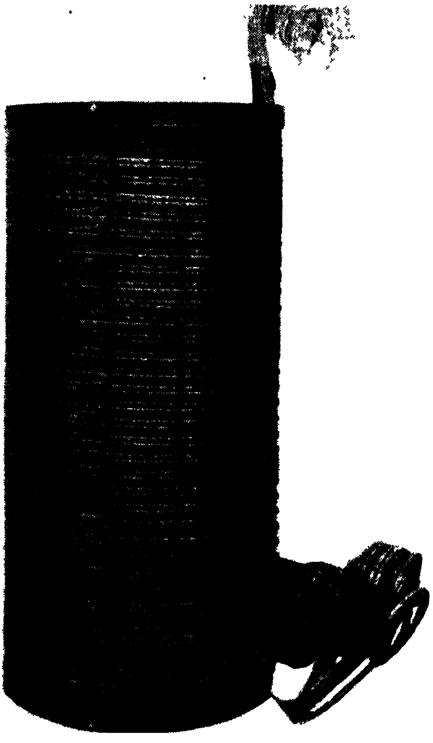


FIG. 27. Coils for one leg of a core-form transformer.

Core-form transformers are usually assembled with the low-voltage winding on the inside, next to the core. This winding, depending on its voltage and current, may be a single cylindrical coil wound on an insulating tube, or it may be made of a number of disk-shaped coils stacked one on top of another with spacers between to allow circulation of the oil. Around the outside of the low-voltage coil is an insulating barrier built up of insulating tubes and oil ducts, and the high-voltage winding is outside this. The high-voltage winding usually consists of a stack of thin flat coils with spacers between them. Figure 27 shows an assembly of coils for one leg of a core-form transformer. The radial spacers between coils and the oil ducts can be seen.

CORES

When an iron core is magnetized by alternating current, it is necessary to supply power continuously to overcome the core loss and maintain the magnetic flux. The amount of power required depends on the frequency, on the characteristics of the iron, and on the magnetic density at which it is worked.

Core Loss. The core loss in transformers consists of two parts. The first part, called *hysteresis*, is the loss caused by the periodic reversal of the direction of the magnetic flux in the core. The second part, called *eddy-current loss*, is caused by local circulating currents in the iron, which flow as a result of voltages induced by the alternating flux. Both these losses appear as heat in the transformer.

Hysteresis is minimized by a proper composition of the iron and by proper annealing. It has been found that the addition of a small percentage of silicon to iron reduces the iron loss and also prevents *aging*, by which is meant a gradual increase of the hysteresis loss over a period of time. Aging always occurred in transformers built before the introduction of silicon steel (about 1910).

Eddy-current losses are reduced by laminating the core in a plane perpendicular to the direction of the eddy currents. This breaks up the path of the circulating current and so reduces its effect. Figure 28A represents a core-form transformer with coils on the two legs. The arrows show the instantaneous direction of the magnetic flux. Figure 28B is a cross section on the line AB, assuming a solid cross section of iron. The dot in the upper yoke represents the point of an arrow indicating the direction of flux toward the observer, out of the plane of the paper. The plus sign in the lower yoke represents the tail of an arrow and indicates flux direction away from the observer, into the plane of the paper. The concentric rings around these symbols show the path of the eddy currents.

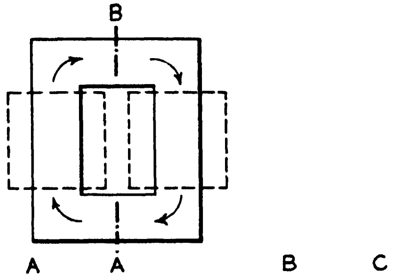


FIG. 28. Magnetic flux in core.

In Fig. 28*C* the iron has been split into two parts insulated from each other. The total flux in the two parts is the same as before, and consequently the operation of the transformer coils is not affected, but in each section only half the flux produces circulating currents. The resistance in the path of the eddy currents is approximately doubled, since the width of the path is only one-half. Assuming each of the quantities in Fig. 28*B* as unity, the following comparison may be made between conditions in Figs. 28*B* and 28*C*.

	Fig. 28*B*	Fig. 28*C*
Flux per section	1	½
Volts per section	1	½
Resistance per section	1	2
Eddy current per section, E/R	1	¼
I^2R per section	1	⅛
I^2R total	1	¼

That is, with iron of half the thickness the eddy-current loss is reduced to a fourth, or the eddy-current loss varies as the square of the thickness of laminations. In actual transformers the laminations are very thin. A common thickness for punchings for 60-cycle transformers is 0.014 inch. Transformers for 25 cycles frequently use punchings 0.025 inch thick.

Magnetizing Current. In addition to the current required to supply the iron losses of the transformer, a component of current out of phase with the voltage is required to magnetize the iron. This is a *wattless current* and does not represent power. It does, however, add to the current in the lines and in the primary winding of the transformer and thus increases the copper loss somewhat.

Exciting Current. The exciting current is the vector sum of the iron-loss current and the magnetizing current. Since these quantities are 90 degrees from each other in phase, their sum is

$$\text{Exciting current} = \sqrt{(\text{iron-loss current})^2 + (\text{magnetizing current})^2}$$

A typical figure for exciting current is 3 to 5 per cent of the rated output of the transformer, although it may be considerably less than this in large power transformers and may sometimes run higher in small distribution transformers.

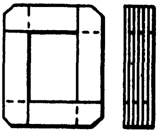


FIG. 29. Core built from I plate.

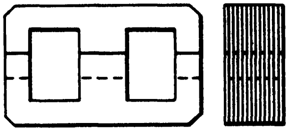


FIG. 30. Core built from E plate.

Construction of Cores. If there is an air gap in the core, the necessary magnetizing current is greatly increased, because air has a much lower permeability than iron. Joints in the iron circuit, therefore, are made as tight as possible, and the joints in adjacent laminations are overlapped, as shown in Fig. 29. The full lines show the joints in alternate layers, and the dotted lines the joints in the intermediate layers. This gives a small effective air gap for the flux to jump and consequently a comparatively small magnetizing current. Even with this arrangement it is necessary to have the punchings butted well together in each layer.

In small transformers the mean turn of iron is small, and the air gap is of more relative importance than in large transformers. To decrease the magnetizing current in small transformers it is customary to decrease the number of air gaps by making punchings of special shapes. Sometimes these punchings take the form of an E, as shown in Fig. 30. Two such punchings are butted together to form a layer, and the joint is overlapped by the punchings in the next layers. Sometimes an L shape is used. Two L's form a layer for the core-form transformers, as shown in Fig. 31, or four L's for the shell form, as in Fig. 32.

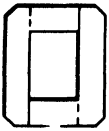


FIG. 31. Core built from L plate.

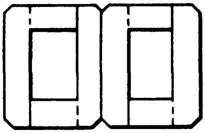


FIG. 32. Shell-form core built from L plate.

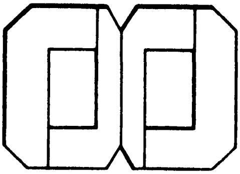


FIG. 33. Core with widened return circuit.

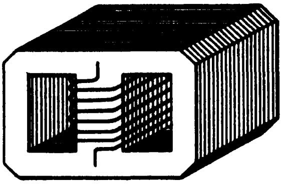


FIG. 34. Shell-form core for rectangular coils

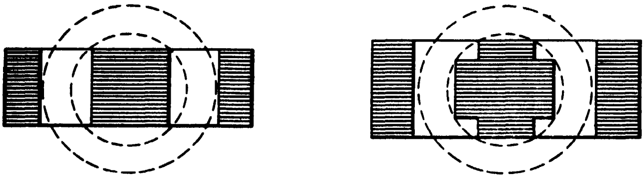


FIG. 35. Shell-form cores for circular coils.

Another scheme for decreasing the magnetizing current and the iron loss as well is to widen the part of the iron which does not pass through the coils. Figure 33 shows punchings of this kind. Widening does not affect the size of the coils, but it does decrease the magnetic-flux density in the widened part of the iron and therefore decreases the iron loss and exciting current. Widening has been used in small distribution transformers.

For large power transformers the iron is always sheared in straight pieces, and no widening is used. This is because the air gap is of less relative importance in such transformers and it is possible to get the desired exciting current more economically without widening.

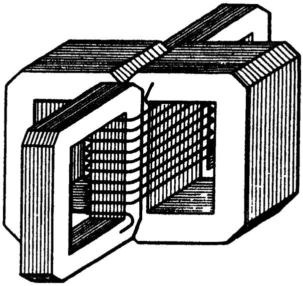


FIG. 36. Shell-form core with four return circuits.

Shell-form Cores. In shell-form transformers a single stack of coils is used. The core passes through the coils and is split into at least two return circuits as shown in Fig. 34. The central leg of shell-form transformers is generally made with a rectangular cross section, to suit rectangular coils, as shown in Fig. 34. Sometimes circular coils are used, and the central leg of the core is made square or cruciform as shown in Fig. 35. The latter form gives a better space factor of the iron in the coil and is therefore more economical of material, but it is somewhat harder to build.

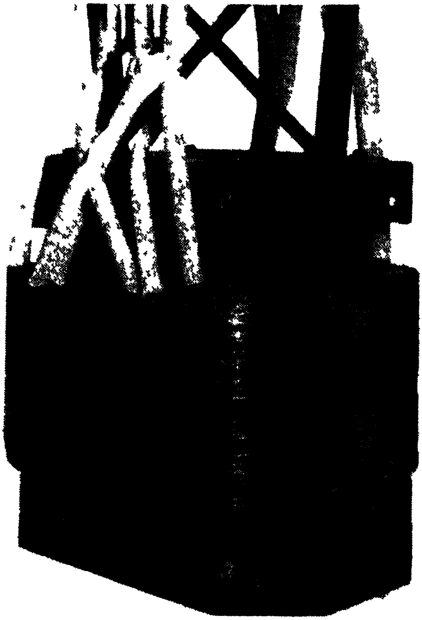


FIG. 37. Small core-form transformer assembled.

In small distribution transformers of the shell form the core is sometimes divided into four return circuits as shown in Fig. 36.

A similar construction has also been used with three return circuits. These designs reduce the mean turn of iron somewhat and thus save a little in the weight of iron and in the iron loss.

A large shell-form transformer, complete with core and end frames, is shown in Fig. 26.

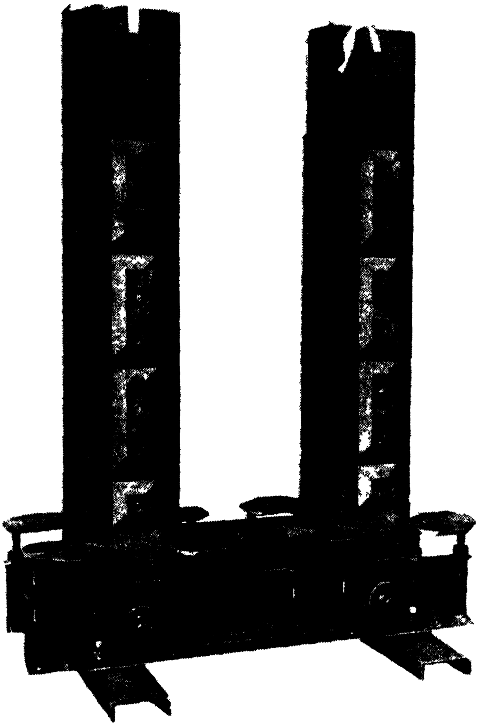


FIG. 38. Core for large core-form transformer.

Core-form Cores. In small core-form transformers the punchings, whether L plates or I plates, are built into the coils in much the same way as the punchings for small shell-form transformers. The end frames are then applied, and the transformer is ready for its final treatment and assembly in the tank. Figure 37 is an example.

For large core-form transformers the punchings for the bottom yoke and the legs are assembled first. Each leg is held together with insulated rivets or bolts, and the bottom yoke is bolted into the end frames. The core is then set upright, and the coils for each leg are lowered into place. Figure 38 shows such a core ready to receive the coils, and Fig. 39 shows a three-phase core-form transformer partly assembled. The core rivets can be seen in the middle leg, the insulating tube is in place on the right leg, and part of the coils are stacked on the left leg. Figure 40 shows how the top yoke is put in place after the coils are installed.

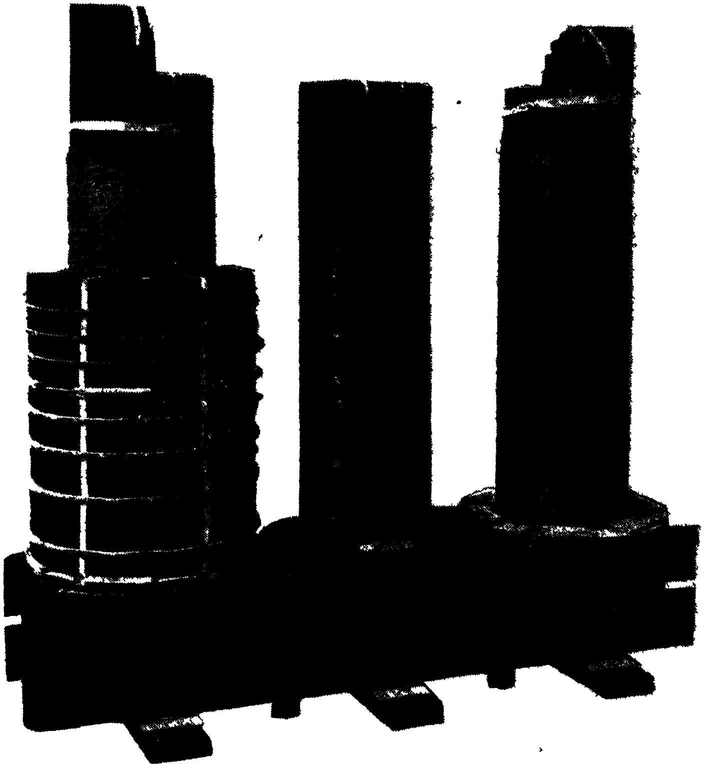


FIG. 39. Three-phase core-form transformer partly assembled.

In order to take full advantage of the superior qualities of the best low-loss, high-permeability transformer iron it is necessary to design cores so that the magnetic flux is always in the same direction as the grain of the iron. This has led to two new core arrangements.

The type C core consists of a strip of iron of the required width wound like a clock spring but around a rectangular mold. The tightly wound coil of iron is annealed and then cemented so that the individual turns adhere firmly together. It is then cut in two, and the cut surfaces are made true and smooth. The two U-shaped pieces thus formed are placed around the coil and held firmly together by steel bands. Figure 41 shows a core of this kind partly assembled with coils to make a shell-form transformer. Type C cores have been used in distribution transformers up to 100 kva and in many instrument transformers.

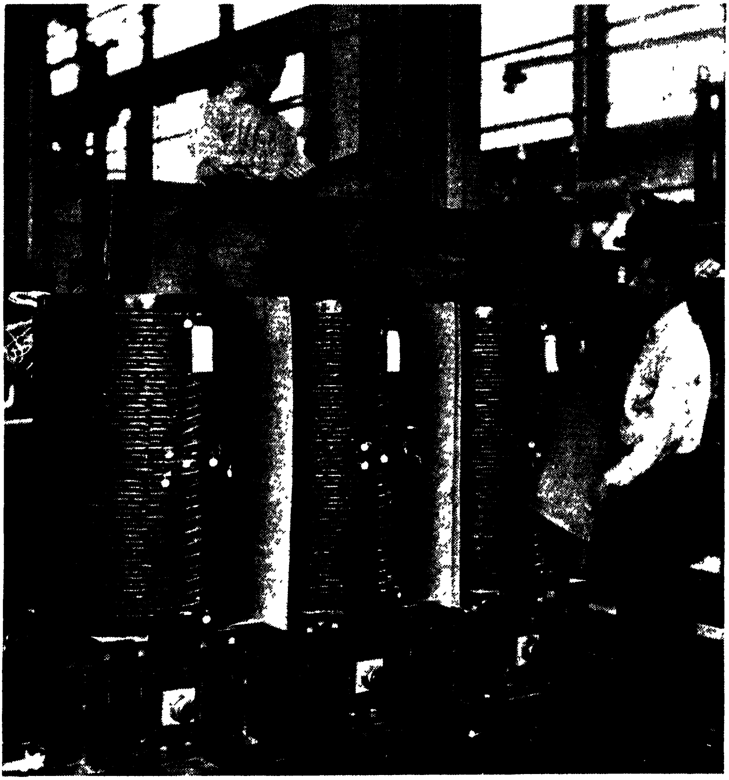


FIG. 40. Building top yoke.

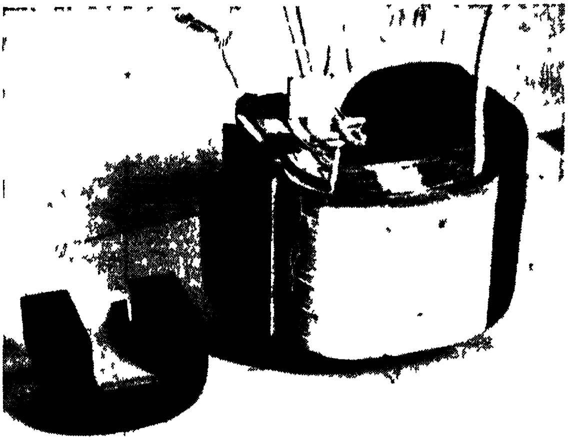


Fig. 41 Type C core partly assembled

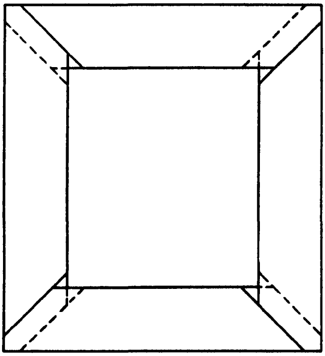


Fig 42 Type D core plates

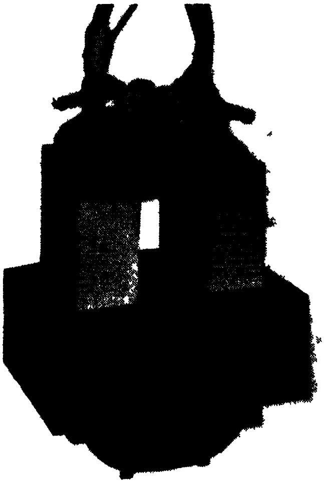


Fig 43 Type D core partly assembled.

Type D cores are built of straight strips, but in order to keep the magnetic flux parallel to the grain of the iron the joints in each layer of laminations are cut at 45 degrees, as shown in Fig. 42. Such cores are used in transformers up to the largest sizes. Figure 43 shows a type D core partly built around a small set of coils.

The coils and core are the working parts of a transformer. Various forms of coils and cores have been developed, and each has a field for which it is best adapted, but in every case the transformer must be designed to have losses low enough to give satisfactory efficiency and must be provided with adequate means of dissipating the losses.

CHAPTER IV

TRANSFORMER COOLING

Energy losses occur in all kinds of electrical apparatus. Transformers are no exception to the rule, although their losses are less in proportion than those of most other electrical machines. The energy losses appear as heat, and one of the problems of transformer design is to provide means for getting rid of the heat. The method used depends on the size of the transformer and on the condition under which it is to be operated.

Dry-type Transformers. Small low-voltage transformers generally operate without oil. In the smaller transformers of this class the coils are wound without ducts. This is possible because a small transformer has a surface that is large in comparison with its volume and the watts to be dissipated per square inch of surface are therefore small. Also, the heat has a short distance to travel to reach the surface, and the interior of the transformer is therefore not much hotter than the surface. Such transformers may or may not be enclosed in metal cases. Figure 44 shows one form of case which has been used. It can be mounted either on a horizontal surface or, by means of the brackets, on a vertical surface. Ventilation is provided by openings around the bottom of the walls and under the overhanging cover. Knockouts are arranged for conduit connections.

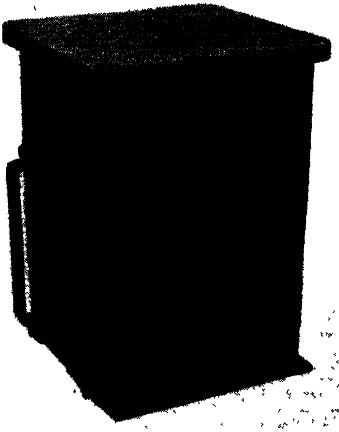


FIG. 44. Case for small dry-type transformer.

Dry-type transformers without air ducts through the coils are used for most of the small instrument transformers, for most small specialty transformers, and for low-voltage distribution transformers up to about 10 kva.

When dry-type transformers are of more than about 10-kva capacity, it becomes difficult to cool them if they are totally enclosed, so steps must be taken to increase the amount of surface exposed to the cooling air. This can be done by assembling the transformer with air ducts between the coils, as explained in Chapter III. The heat from the coils warms the air in the ducts, and it rises, while the cooler air from below the transformer enters the ducts. The convection current thus set up carries the heat away from the inside of the coils, thus supplementing the exterior cooling surface of the transformer.

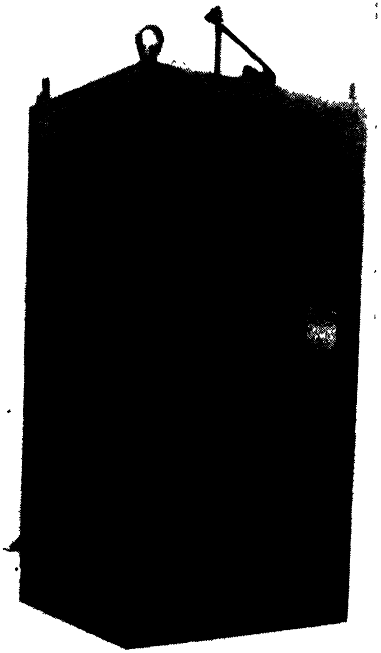


FIG. 45. Air-blast transformer through which air is forced by a blower.

Dry-type self-cooled transformers for indoor operation have been made up to 2,000 kva and 14,400 volts. These large sizes are core form with large areas of ventilating ducts between and around the coils. Figure 18 shows a 11,500-volt, 333-kva, single-phase transformer with its case removed. The large open spaces between the coils can be seen, and there are large vertical ducts between the high-voltage winding and the low-voltage winding on each phase.

Air-blast Transformers. An extension of the principle of the ventilated dry-type transformer is shown in Fig. 45. It is somewhat similar to the small ventilated dry-type transformer, but many air ducts are built into its core and coils, and the transformer is completely enclosed in a sheet-metal housing. It is installed over a hole in the floor through which air at a few ounces pressure is supplied from a blower. The flow of air through the transformer is regulated by a damper, the handle of which can be seen in the picture. The small window at the bottom is used to inspect the leads and connections.

Air-blast transformers are used in certain substations where large quantities of oil are prohibited because of fire hazard. A modified form of air-blast transformer is used on many electric locomotives because of the relatively small size and light weight.

Since the introduction of air-insulated self-cooled transformers and of askarel-filled transformers the number of new air-blast transformers has been relatively small.

Oil-immersed Self-cooled Transformers. In general, transformers too large for cooling by natural ventilation are immersed in oil, and even small transformers, especially those for use out of doors or on high-voltage circuits, are often built for oil immersion. Figure 46 shows tanks for small oil-insulated distribution transformers. The transformer is fastened inside the tank, which is filled with a special grade of oil. The oil not only helps to cool the transformer but also forms a part of the insulation of the windings. As a cooling medium, the oil acts by means of convection currents which circulate the oil up along the heated parts of the transformer, where it absorbs heat, and then down along the cooler surface of the tank, where it gives up heat. The oil thus transfers heat from the transformer to the tank wall, where it is dissipated into the surrounding air.

In small oil-cooled transformers, a tank which is large enough to contain the transformer mechanically has sufficient surface to dispose of the heat generated in the winding and core. The amount of material in a transformer increases as the cube of its dimensions, whereas the tank surface increases as the square. As transformer sizes are increased, therefore, the amount of material and consequently the loss in the transformer increases faster than the tank surface. A point is soon reached where the tank surface cannot dissipate the heat, and means to increase its ability to do so must be applied.

The first expedient that would occur to a designer would probably be to increase the height of the tank and thus provide more surface, and this is often done. This method takes an increased amount of oil, but it retains the simplicity of the plain tank and does not increase the floor space.

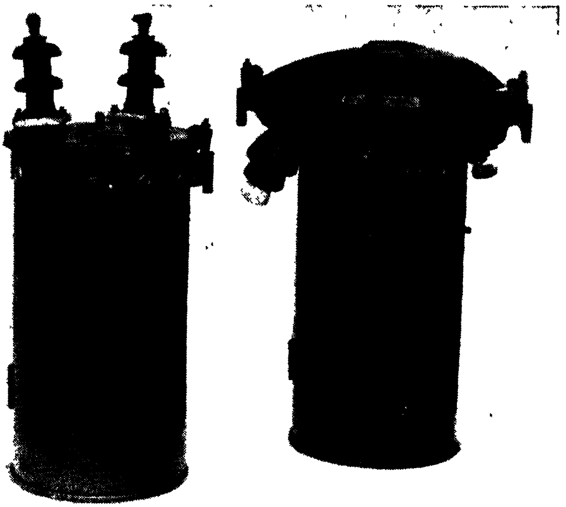


FIG. 46. Small distribution transformer, showing two methods of arranging bushings.

In another design the surface of the tank is corrugated. This helps, although a square inch of corrugated wall is not worth so much for cooling as a square inch on a flat-walled tank. The cooling air does not circulate so freely against the corrugations as against a flat surface, and a certain amount of heat radiated by the corrugations is absorbed by adjacent corrugations. This type of tank has been much used, however. It enables the exposed surface of the tank to be very largely increased without much of an increase in either the floor space or the oil.

A more recent method is to weld fins to the tank wall, as shown in Fig. 47. Such fins require no additional oil, and they add less weight than corrugations to dissipate the same heat.

Still another way to increase the exposed surface of tanks is by use of tubes. They are sometimes bent at both ends and welded at the top and bottom into holes in the tank wall. Figure 48 shows a tubular tank. Sometimes tanks are made with a single row of tubes and sometimes with two or three rows, one outside the other, depending on the amount of heat to be dissipated.

Fig. 47. Distribution transformer with cooling fins.

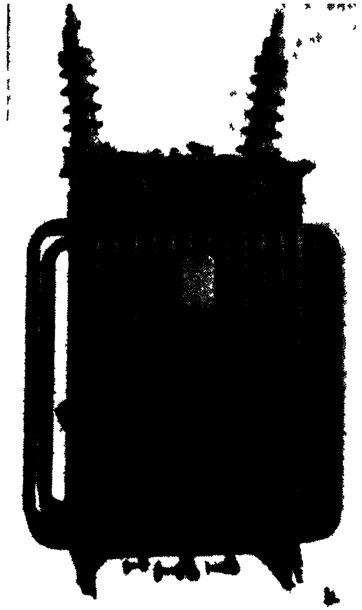


Fig. 48. Tank with tubular cooling.

Another form of tubular cooler is made by welding several vertical tubes into headers at the top and bottom. The headers, in turn, are welded into holes in the tank wall. Figure 49 shows this construction.

Transformers too large to be cooled economically by corrugated or tubular tanks are mounted in boiler iron tanks provided with radiators, as in Fig. 50. The radiators are connected to the tank at the top and bottom, so that the hot oil flows from the top of the tank into the radiator. Here it is cooled and returns to the bottom of the tank ready to rise through the warm ducts of the transformer and repeat the cycle.

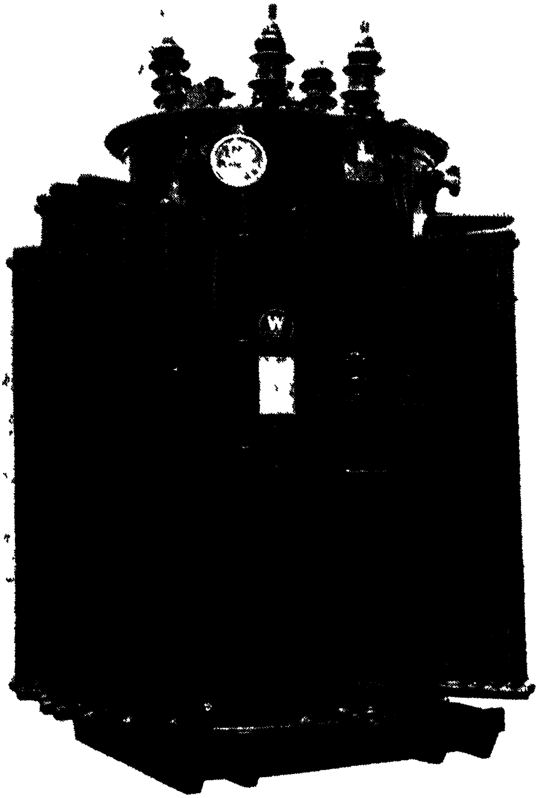


FIG. 49. Tank with tubular coolers

Many forms of radiator have been used, and the present forms are so effective that self-cooled transformers in any required size can be built. A special form of small radiator called a *cooler* is shown on the tank in Fig. 51. Two long narrow steel plates are welded together around the edges, leaving a small opening at each end. The plates are also stitched together by welding down the center. The cooler is then blown up by air or hydraulic pressure. This expands the cooler to the form shown and makes passages for the oil through it.

Transformer Tanks. The purpose of the tank for a large transformer is to contain the transformer and its oil and to support the cooling means. Several forms of tank have been used. Many transformers are mounted in round tanks. Oval tanks, rectangular tanks, and eight-sided tanks also have been used. The smaller the tank for a given transformer the less oil will be required and the lighter will be the complete assembly. With this in mind the *form-fit* tank was devised for large shell-form transformers, and it has been used extensively. The base of the tank is a deep pan which contains the lower end of the assembled coils (see Fig.

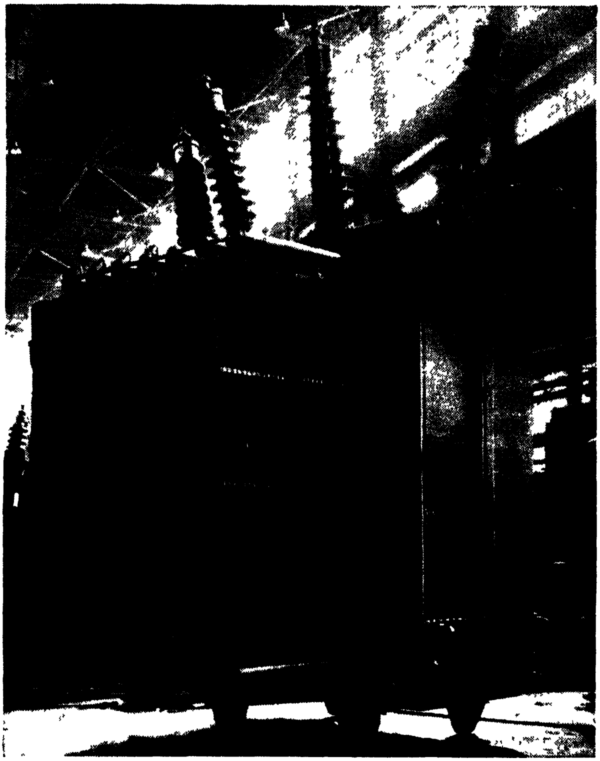


FIG. 50. Tank with radiators.

52, which is a cutaway view showing the construction). The top of the tank base is a flat ledge on which the punchings are built and which extends outside the punchings in all directions. The upper part of the tank fits like a cap around the punching stack, with suitable clearance.

In order to stand the vacuum which is applied while the transformer is being filled with oil the upper part of the tank must be reinforced. This is accomplished by welding channel-shaped braces to the tank walls where required. Channel braces inside the tank are located so that, when the tank is closed, they will bear against the upper surface of the punching stack. The need for separate end frames is thus removed, and a saving in weight is made.

When the upper part of the tank has been put in place, the inside bracing channels rest on the punching stack and the bottom of the wall almost touches the flat ledge on the tank base. The top section is then drawn down tight with clamps and welded all around to the base. This makes a rigid and perfectly sealed assembly and contains a minimum amount of oil. Radiators are attached above and below the welded joint, as shown in the figure.

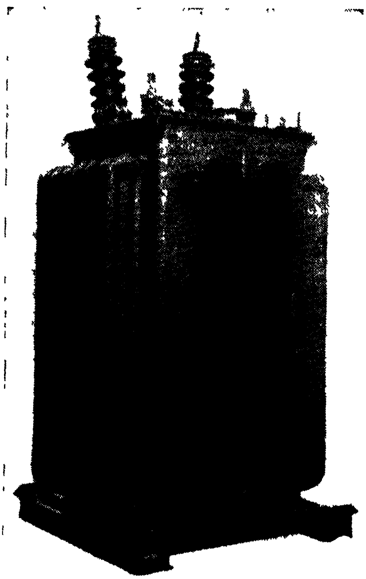


FIG. 51. Tank with flat coolers.

Self-cooled Transformers with Air Blast. If the convection current of air along a heated surface can be broken up so that the heated air is driven away from the surface and replaced with cool air in rapid motion, the effectiveness of the cooling system is increased. The practical embodiment of this idea may take several forms. In one form (Fig. 53) a single large motor-driven fan is used. The discharge from the fan is led into an air duct that surrounds the whole tank. From the air duct nozzles are led off to blow against each radiator.

Figure 54 shows another method of accomplishing the same result. A small housing of sheet metal covers a small space near the center of the radiator. At the outer end of the housing is an electric fan similar to the fans used generally in houses and offices. This blows air through the housing and cools the radiator.

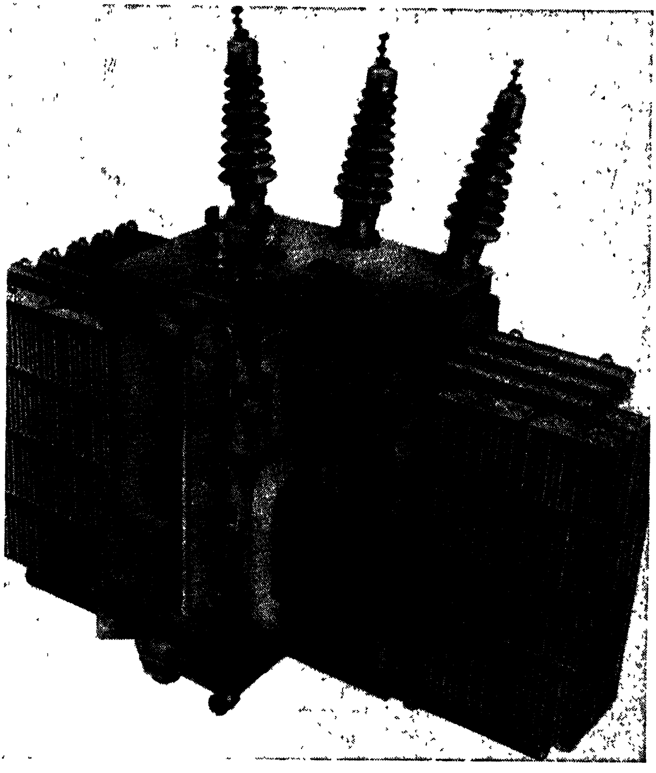


FIG. 52. Large three-phase transformer in form-fit tank, cut away to show construction.

Still another arrangement is to mount a number of radiators parallel to one another and to use several fans to blow air through the whole group. Figure 55 shows such an assembly. By this scheme the allowable output of the transformer is frequently increased by one-third.

Forced-oil System. A scheme which is used occasionally is to pump oil out of the transformer tank and into a cooling device

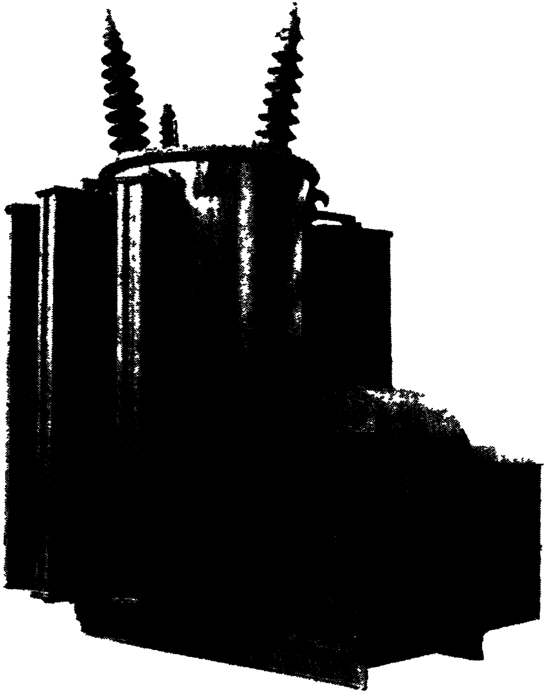


FIG. 53. Large fan blowing air over the radiators.

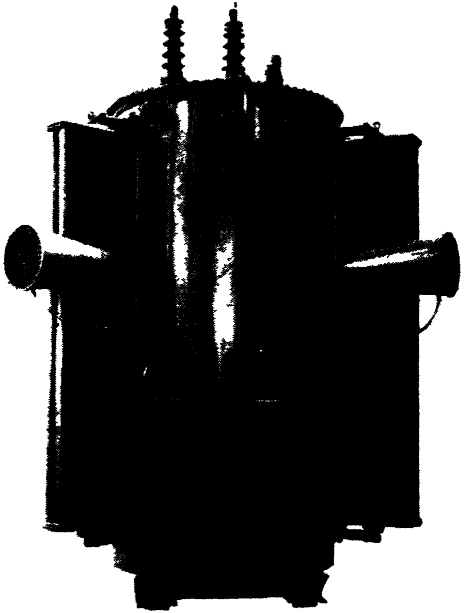


FIG 54. Small fan installed on each radiator.

separated from the transformer. This may be piping submerged in a convenient lake or stream. The pump should be connected so that the oil in the cooling system will be under pressure and not under suction, so that a possible leak will not cause water to enter the transformer. This scheme is rarely used in this country.

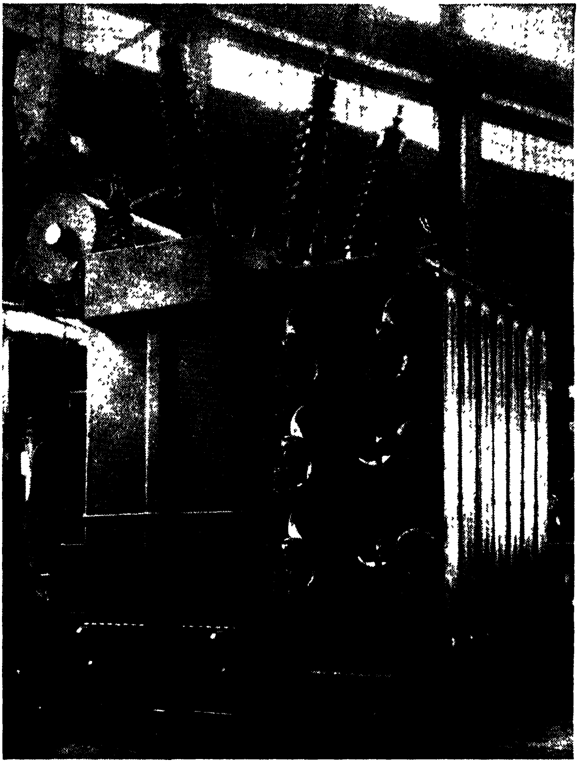


FIG. 55. Tank with fan-cooled radiator bank.

Forced-oil–forced-air System. A modification of the forced-oil system was brought about, at least partly, by the scarcity of materials during the war. The transformer is mounted in its tank in such a way that very little oil can flow around the core, most of the oil being forced through the ducts between the coils. A centrifugal pump is used to circulate the oil rapidly through the ducts and through an external cooler attached to the transformer. The cooler consists of a nest of tubes with fins on the outside to increase the surface. Fans force a blast of air around the tubes. The result is an efficient cooling system which materially increases the amount of power that can be handled by a transformer of a given size. Figure 56 shows a transformer of this kind. In this example, to save height, the transformer is laid on its side in the tank and the oil is pumped out of one end of the tank, through the cooler, and into the other end.

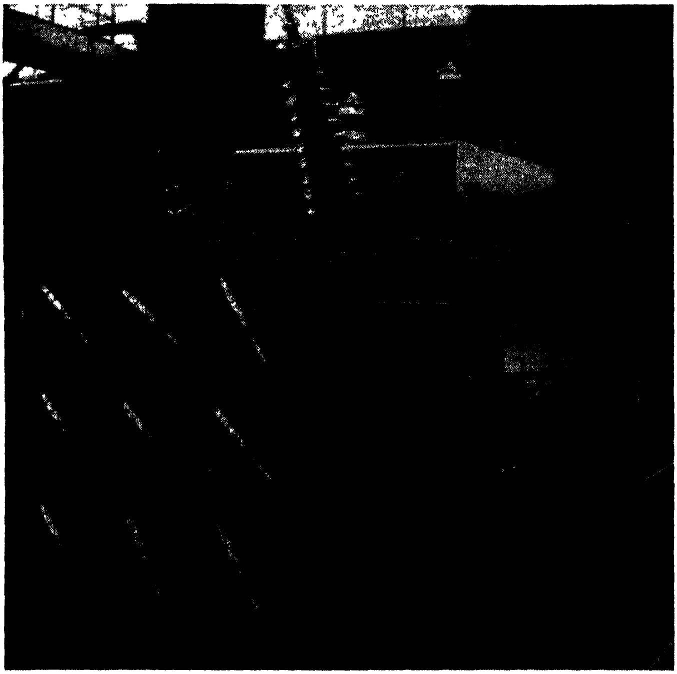


FIG. 56. Forced-air-forced-oil transformer.

A transformer of this type can be mounted on a truck, with suitable lightning arresters and control apparatus, to form a portable unit. Such units are useful when a substation is to be modified, when a temporary load is to be connected, or when extra power is required from an existing substation. Figure 56*A* is an example of this arrangement.

Fans and pumps can be applied, with equally good results, to conventional transformers with radiators if the oil is forced to flow mainly through the ducts between the coils.

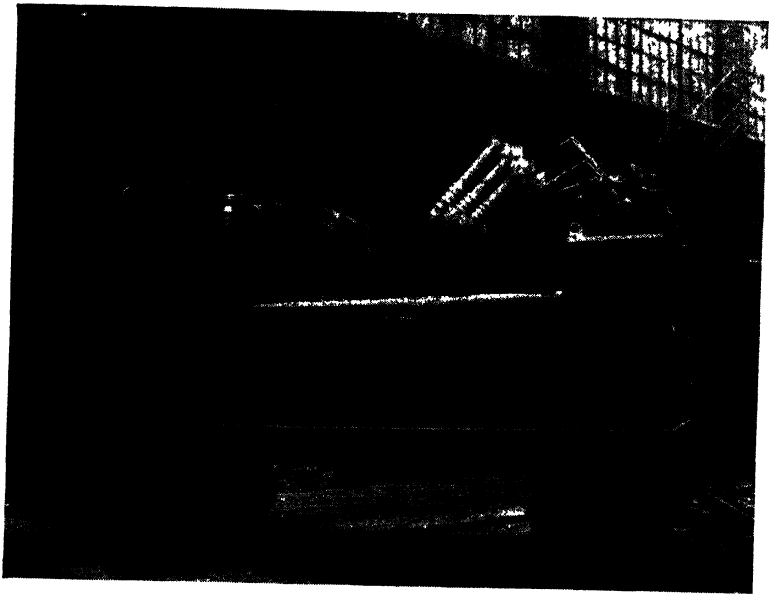


Fig 56A Portable transformer

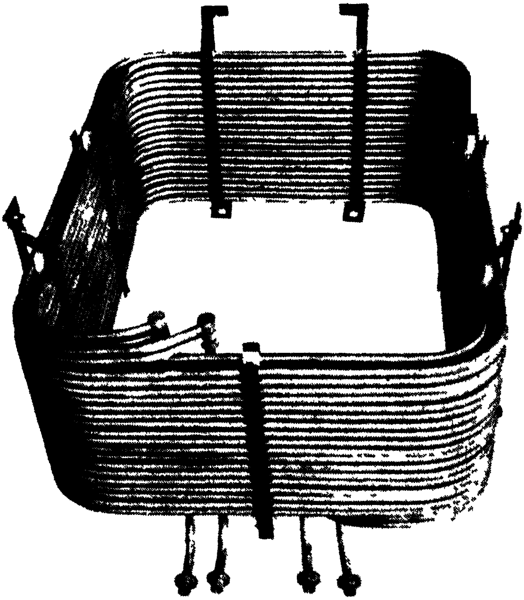


Fig 57 Water-cooling coils

Water Cooling. Water cooling of transformers deserves mention, although it is not so much used at present as the methods previously described. A coil of pipe, usually copper, is placed inside the tank just below the surface of the oil. The ends of the pipe extend out through the tank wall and are connected to a water system, so that water flows through the pipe while the transformer is operating. The hot oil rising from the transformer comes in contact with the cool pipes and gives up its heat, which is carried away by the water. Figure 57 is a typical cooling coil, and Fig. 58 shows a large water-cooled transformer.

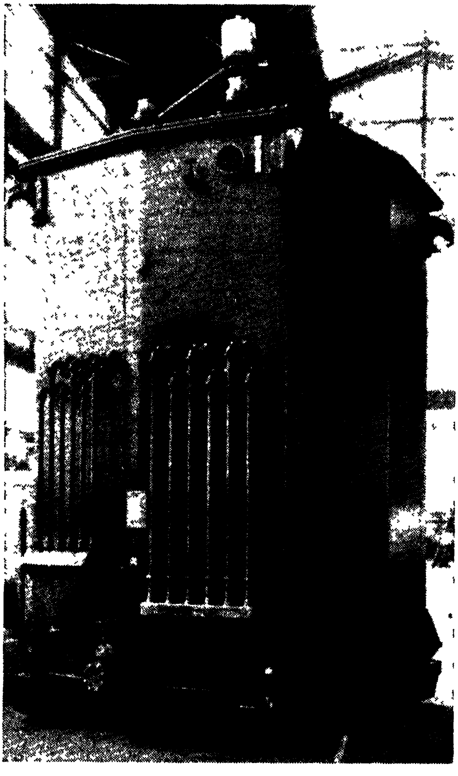


Fig. 58. Large water-cooled transformer.

It is difficult to find room in a form-fit tank for water coils, so external coolers are used. The cooling coils are mounted in external containers, and the oil is led by large pipes to flow around the cooling coils and back into the bottom of the tank. Sometimes centrifugal pumps are connected in the pipes to force a rapid circulation of the oil and thus increase the capacity of the transformer. Figure 58*A* shows a large transformer equipped with external water coolers.

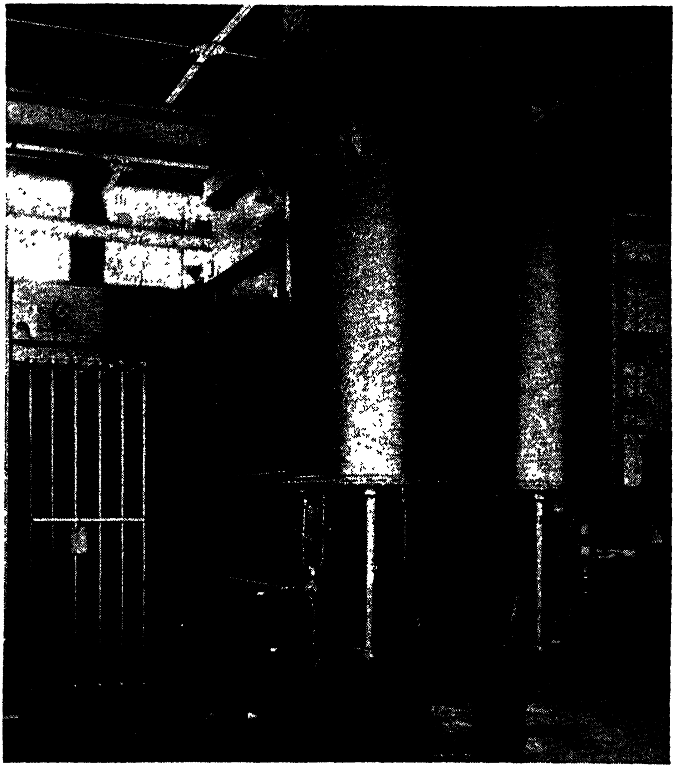


FIG. 58*A*. Water-cooled transformer with external coolers.

Water cooling is very effective, and it results in transformers which are smaller and cheaper than those cooled by radiators, but its principal use is where water is plentiful and cheap, and it must be guarded in winter against the possibility of frozen pipes.

Summary. The whole problem of transformer cooling is to remove the heat caused by the transformer losses from the coils and core, where it is produced, and to dissipate it into the atmosphere. In self-cooled transformers this dissipation occurs by radiation and by convection currents of air around the transformer itself or around its tank and radiators. Transformers of the smallest size have sufficient surface of their own to dissipate their losses. For larger transformers additional ventilation must be supplied, or the transformer must be immersed in oil, which serves the twofold purpose of helping to insulate the transformer and transferring the heat from the transformer to the cooling surfaces.

Various methods are used to get sufficient surface to dispose of the heat. Besides the self-cooled transformers, water-cooled types are used. These require cheap and abundant water and attention to prevent freezing.

CHAPTER V

TEMPERATURE INDICATORS

The life of a transformer depends on the life of its insulation, and the life of the insulation depends on the maximum temperature at which it is run and on the time that such temperature is maintained. It is therefore important to keep the temperature of the hottest spot in the windings below the danger point, and as a means to this end it is important to know the actual temperature in the windings.

Oil-temperature Indicators. The most obvious indicator of the transformer temperature is the temperature of the hot oil above the transformer, and several devices have been marketed to show this temperature. A good example of this class of indicator is the dial-type thermometer. The bulb of the thermometer is mounted in the hot oil, and the dial is mounted outside the tank. In one form the dial is provided with two hands, a black hand which indicates the present temperature and a red hand which is driven up the scale by the black hand but is released when the temperature decreases. The red hand therefore shows the highest temperature reached by the oil since the last setting. It can be reset by means of a knob at the front or in some designs by means of a magnet. Such thermometers are made with or without alarm contacts. A modification of this type of thermometer is made with the dial tilted forward at an angle, so that it can be attached to a pole-type transformer and read from the ground. Figure 59 shows a dial-type thermometer.

WINDING-TEMPERATURE INDICATORS

Notwithstanding its convenience, the oil temperature is not a reliable measure of the winding temperature. A sudden heavy overload will cause the copper temperature to rise more rapidly than the oil temperature, and it is quite possible for the copper to reach a dangerous temperature before the oil gives any warning. The copper temperature may be thought of as made up of three parts, the *ambient temperature,* or the temperature of the surrounding air; the oil rise above the ambient temperature; and the temperature gradient from the copper to the oil. This last part is not included in the oil temperature, and it goes up rapidly as the load increases. It is therefore very desirable to have an indicator which will show the actual temperature of the hot spot in the windings, and such an indicator can be produced in several ways.

Embedded Resistor. One scheme for getting the actual coil temperature is to place a resistance element between turns of the transformer winding at what is estimated to be the hottest spot. Knowing the resistance of this element at a given temperature, its resistance at any other temperature can be used to indicate the temperature. If the voltage of the winding in which the resistance element is placed is too high to be brought to the instrument, an insulating transformer is connected between the resistance element and the measuring circuit. Figure 60 is a diagram of the circuit. It is a kind of bridge circuit. As the resistance of R changes with respect to R', the potential of the point B changes with respect to that of the point A, so that the current in the movable coil of the meter will be changed or reversed. The scale of the meter is calibrated in degrees centigrade, and the calibration includes the conventional allowance of 10° for the hottest spot, as required by the AIEE rules.

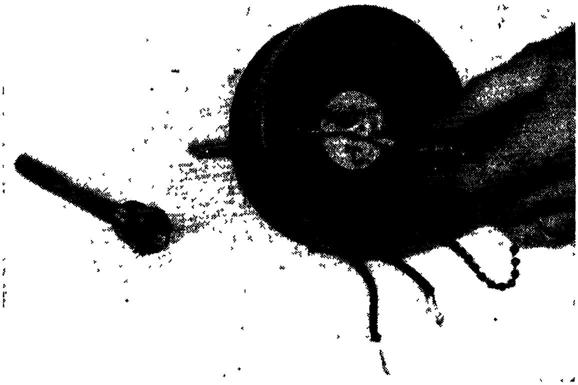


FIG 59. Dial-type thermometer.

This scheme is satisfactorily accurate, but it has the disadvantage that the resistance element must be put into one of the transformer coils, and its leads to the insulating transformer must be insulated for the same voltage as the transformer coil.

Dial-type Hottest-spot Indicator. Another type of hot-spot indicator is shown in Fig. 61. It consists of a dial-type thermometer with a high-resistance metal bulb. A current transformer mounted inside the case of the power transformer and energized by the current in one of the windings of the power transformer is connected to the metal bulb of the thermometer. The bulb thus carries current proportional to the load on the main transformer. It is located in the hottest part of the oil and in addition is surrounded with heat-insulating material to make the temperature difference between the bulb and the oil approximately the same as that between the coils and the oil. The thermometer bulb is therefore affected by the same influences which affect the transformer windings, and the thermometer will give a good indication of the temperature of the coils. The dial of the thermometer is calibrated to read 10° higher than the actual temperature of the bulb, so that the reading will include the 10° conventional hot-spot allowance.

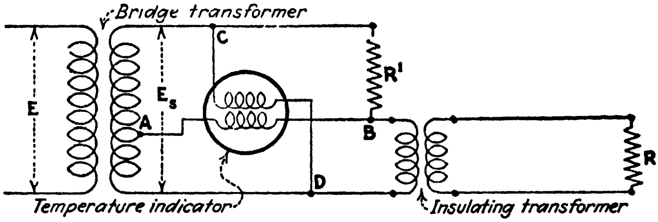


FIG 60. Diagram of alternating-current bridge-type temperature indicator.

This scheme has the advantage that the whole of the temperature-indicating apparatus is electrically separate from the transformer windings. The current transformer which supplies the heating current for the thermometer bulb is usually of the ring type and is mounted around the grounded portion of the transformer bushing, just under the cover of the transformer tank, so that it is effectively shielded from the line voltage.

Switchboard-type Hottest-spot Indicator. Still another type of hottest-spot indicator is used where an indication is desired at some distance from the transformer. This is shown diagrammatically in Fig. 62. It is similar in principle to the embedded resistor, but the resistance element, instead of being embedded in one of the transformer coils, is mounted in a special heating coil, which is supported in the hot transformer oil. The heating coil is fed by a current transformer and is thermally insulated so that it takes approximately the same temperature rise above the oil as the transformer coils. The resistance element inside the heating coil is connected to a bridge circuit as shown. The meter in the bridge circuit is calibrated in degrees, and the calibration includes the 10° hot-spot allowance. In this scheme as in the preceding one, a ring-type current transformer is generally used to supply the heating current, and the temperature-indicating circuits are completely isolated from the power circuits.

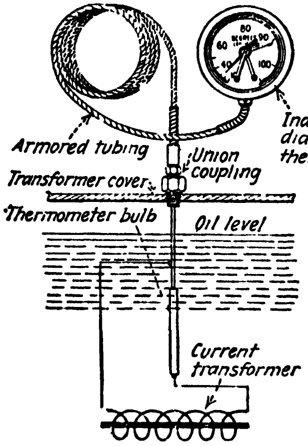


FIG. 61

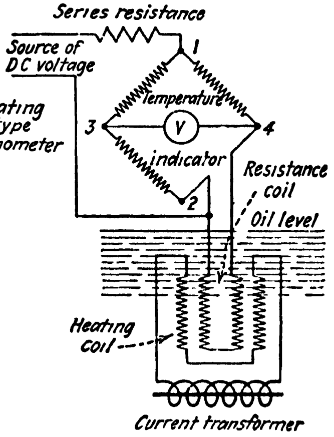


FIG. 62

FIG. 61. Hottest-spot temperature indicator.

FIG. 62. Diagram of bridge-type hottest-spot temperature indicator.

Thermal Relay. A thermal device which has considerable application is a temperature-sensitive relay. It takes into account both the ambient temperature and the temperature rise of the transformer. One form of such a relay consists of a bimetal strip made of two metals having different rates of expansion with heat. The bimetal is mounted in the hot oil and carries current proportional to the load current in the winding. The temperature of the bimetal thus corresponds closely to the temperature of the copper in the winding. As the bimetal is heated, it expands more rapidly on one side than on the other, and consequently the strip bends. When its temperature indicates that the winding has reached its maximum safe temperature, the bimetal operates a trigger which closes a contact and gives an alarm. If the temperature continues to rise, the bimetal closes a second contact which can be used to trip a circuit breaker. Such a relay thus permits the transformer to carry its maximum safe load at all times, gives a warning if the safe load is exceeded, and can be used to disconnect the load before a dangerous temperature is reached.

CHAPTER VI

RATIO ADJUSTMENT

It is often desirable to change the ratio of a transformer, sometimes to adjust for the voltage drop in a feeder or main, sometimes to adapt the voltage to the varying requirements of a certain load, and sometimes to control the division of the wattless current between two transformers or systems which are operating in parallel. The earliest and simplest scheme for ratio adjustment was to bring taps from one or both windings to a terminal board below the oil level and to provide an arrangement of studs and links by which the connections could be changed. This scheme is effective, but in order to change connections it is necessary to disconnect the transformer from the lines, open the cover, loosen the nuts on the terminal board, and change the position of the links one by one under the oil. This is rather a long and unpleasant job, and probably such changes are made as seldom as possible.

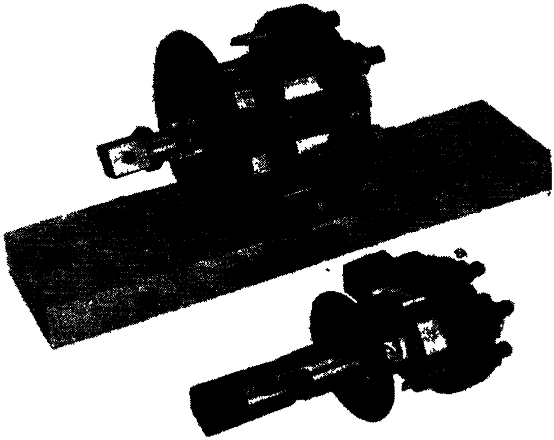


FIG. 63. Small no-load tap changer.

No-load Tap Changer. The first step toward more convenient ratio adjustment was the development of a *no-load tap changer,* or *ratio adjuster.* This consists of some kind of selector switch to which the taps from the windings are connected and which is operated by an insulated handle reaching above the oil and sometimes outside the transformer case or cover. One form of selector switch is shown in Fig. 63. It consists of six brass or copper terminals mounted on an insulating base and a contactor mounted on an arm attached to a shaft, as shown. As the shaft is turned from one position to the next, the contactor connects adjacent pairs of the stationary terminals. Figure 64 is a diagram of connections for this type of tap changer. Taps are brought out of the middle part of the winding and connected to the terminals of the tap changer. With the contactor in the position shown, making connection between leads 3 and 4, all the turns in both parts of the winding are in use. If the contactor is moved one point to the right, it makes connection between 4 and 2, thus cutting out the part of the winding between 2 and 3. The next step cuts out the part of the winding between 4 and 5, etc., step by step, until the final position where 1 and 6 are connected together, leaving the minimum number of active turns in the winding.

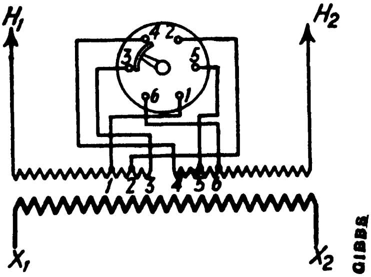


Fig. 64. Diagram of connections for no-load tap changer.

This type of tap changer is designed for use under oil and is not designed for breaking the circuit. It should never be operated until the transformer has been disconnected from the line. For small distribution transformers the operating handle is sometimes located inside the tank above the oil level. The covers of such transformers are small and light, and it is easy to remove them and change taps when necessary. In larger transformers the operating shaft is brought out through an airtight and oiltight gland in the cover, and a handwheel or other driving mechanism and a position indicator are located outside.

The same principle is used generally for no-load tap changers, but the details of construction are adapted to the current which the device must carry and to the voltage between taps. Figure 65 shows a similar tap changer, designed for heavier currents and higher voltages. The creepage distance between live points is increased by putting insulating spacers between the heads of the studs and the mounting plate and also between the mounting plate and the nuts on the studs. Inside these spacers the body of the stud is covered by an insulating tube. Figure 66 shows two decks of a tap changer for a three-phase transformer.

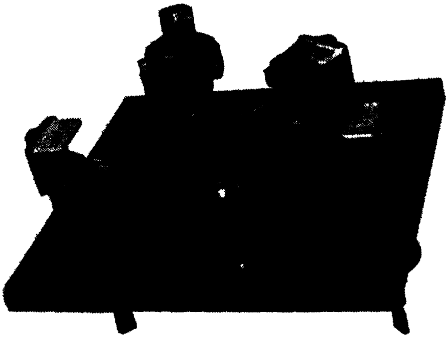


Fig. 65. No-load tap changer for large currents.

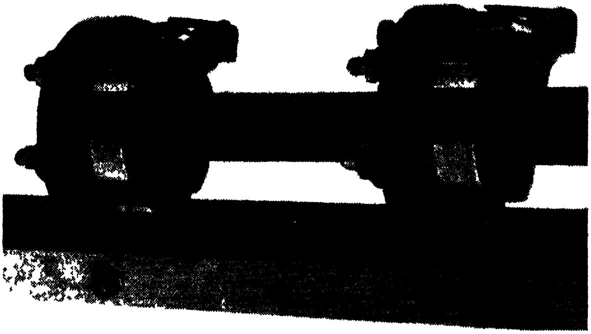
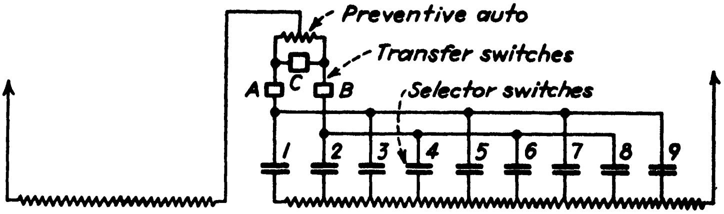


Fig. 66. Two decks of a tap changer for a three-phase transformer.

Tap Changers under Load. The success of no-load tap changers led to a demand for tap changers which could be operated without disconnecting the transformer from the line. Such tap changers have been developed and are in extensive use. The principle on which all modern tap changers under load operate is the use of a preventive autotransformer in stepping from tap to tap on the transformer winding. One embodiment of the principle is shown in Fig. 67. The switches 1, 2, 3, 4, etc., are called *selector switches*. They are never used to make or break the circuit and can therefore be put in the same enclosure as the transformer itself. The switches A, B, and C are called *transfer switches*. They serve to make and break the circuit and are therefore mounted in a separate compartment, so that the oil in which they operate can be cleaned and renewed from time to time as it becomes contaminated from the switching arcs. When selector switch 1 and the transfer switches A and C are closed, the voltage at the middle of the preventive autotransformer is the same as the voltage at the end of the winding 1. To step to the next tap the switches are operated in the following order:



Sequence of switches

Position	1		2		3		4		5		6		7		8		9
Switch No. 1	o	o															
" 2		o	o	o													
" 3				o	o	o											
" 4						o	o	o									
" 5								o	o	o							
" 6										o	o	o					
" 7												o	o	o			
" 8														o	o	o	
" 9																o	o
" A	o	o		o	o	o		o	o	o		o	o	o		o	o
" B		o	o	o		o	o	o		o	o	o		o	o	o	
" C	o		o		o		o		o		o		o		o		o

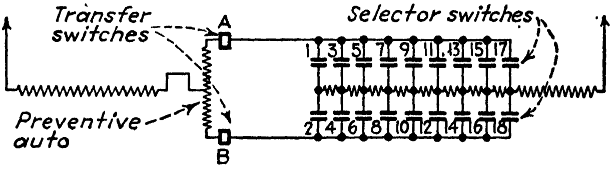
o Switch closed

FIG. 67. Schematic diagram of tap changer under load.

1. Open switch C.
2. Close switch 2.
3. Close switch B.
4. Open switch A.

5. Close switch *C*.
6. Open switch 1.

The middle point of the autotransformer is now at the same voltage as tap 2, and the part of the winding from 1 to 2 is idle. The sequence of switches for the other tap changes is shown in the figure. The selector switches always close before the corresponding transfer switches and always open after the transfer switch has opened. This scheme requires one selector switch for each tap on the transformer and three transfer switches.



Sequence of switches

Position	1				2				3				4				5				6				7				8				9
Switch No 1	o																																
" 2	o	o	o																														
" 3			o	o	o																												
" 4					o	o	o																										
" 5							o	o	o																								
" 6									o	o	o																						
" 7											o	o	o																				
" 8													o	o	o																		
" 9															o	o	o																
" 10																	o	o	o														
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" 15																											o	o	o				
" 16																													o	o	o		
" 17																															o	o	o
" 18																																	o
" A	o		o	o	o		o	o	o		o	o	o		o	o	o		o	o	o		o	o	o		o	o	o		o	o	o
" B	o	o	o		o	o	o		o	o	o		o	o	o		o	o	o		o	o	o		o	o	o		o	o	o		o

o Switch closed

FIG. 68. Schematic diagram of tap changer under load.

When switch *C* is closed, both ends of the preventive autotransformer are at the same potential, and one-half of the load current flows through each half. Since these currents flow around the core in opposite directions, only a negligible reactance drop is introduced into the circuit by the autotransformer under this condition. When switch *C* is open and one of the other transfer switches is open at the same time, during the instant of transition, the whole load current flows through one-half of the preventive autotransformer winding. To prevent an undesirable dip in voltage at this instant the preventive autotransformer is built with an air gap in its core. This prevents the core from saturating and causing an excessive voltage drop in the coil.

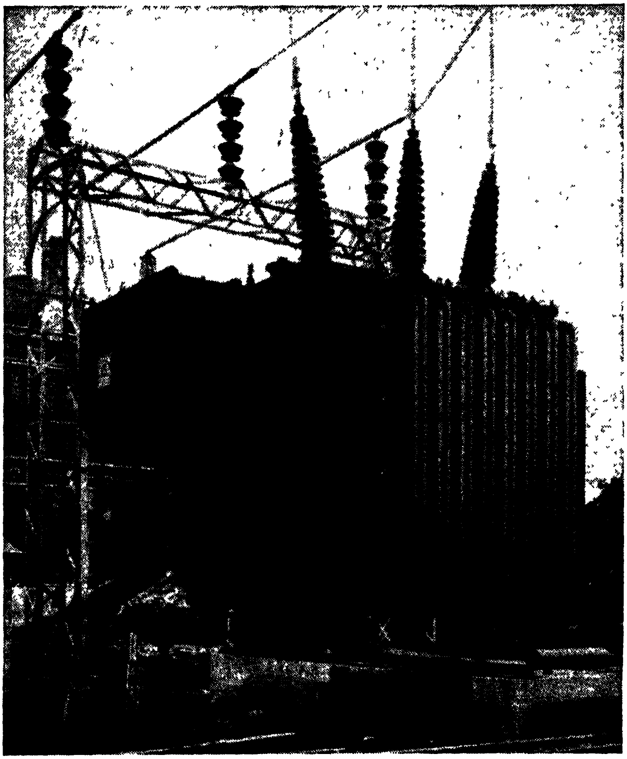


Fig. 69. Transformer equipped with tap changing under load.

A slightly different method of accomplishing the same result is shown in Fig. 68. This scheme requires two selector switches for each tap on the transformer and two transfer switches.

The operation of tap changers under load can be controlled either manually or automatically. For large tap changers the control

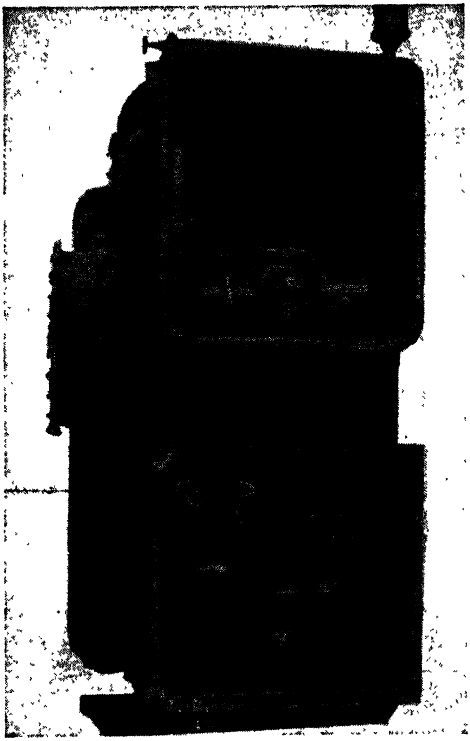
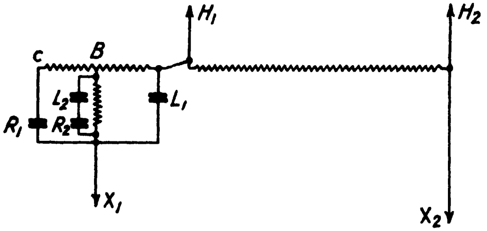


FIG. 70. Operating mechanism for tap changer under load.



Sequence of switches

Position	No boost	1 step boost	2 steps boost
Switch R_1			o
" R_2	o	o	
" L_1	o		
" L_2		o	o

o Switch closed

FIG. 71. Schematic diagram, automatic voltage booster.

mechanism is mounted in a box attached to the side of the transformer case. This box contains the relays and the driving motor for operating the switches. The motor drives a shaft which runs up into a second box containing the transfer switches. Here it is connected by positive gearing to the transfer switches and to the selector switches, located inside the transformer tank. The switches are thus opened and closed positively and are compelled to operate in their proper sequence. A time-delay device is used in connection with the control relay to prevent operation during short dips of voltage. Figure 69 shows a transformer equipped with tap-changer apparatus, and Fig. 70 shows the operating mechanism.

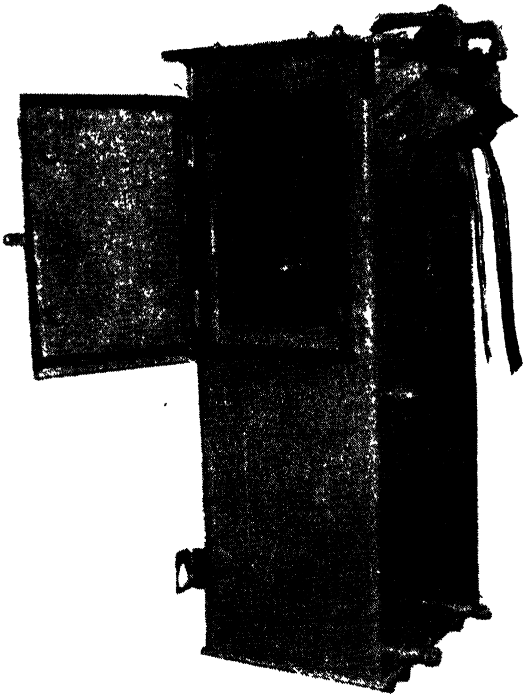


FIG. 72. Automatic voltage booster.

Voltage Booster. Perhaps the simplest application of the idea of the tap changer under load is in the automatic voltage booster, which is intended to adjust the voltage of a feeder as the load changes. It consists of an autotransformer with two steps of boost, a preventive coil, and the necessary switches. The operation of the switches is controlled by a voltage relay. Figure 71 is a schematic diagram, and Fig. 72 is a view of the booster, with the control-compartment door open, showing the voltage relay and the time-delay element. Referring to Fig. 71 switch L_1 is mechanically interlocked with switch L_2 so that one closes the instant after the other opens. Similarly, R_1 is interlocked with R_2. At the position of no boost, switch L_1 is closed and consequently L_2 is open. Line X_1 therefore is connected directly to H_1, and the preventive autotransformer is shunted across a part of the booster autotransformer winding. In passing to the next step the switch L_1 opens and switch L_2 closes. During the instant when both switches are open, the preventive autotransformer carries the load current, but as soon as L_2 closes, the preventive autotransformer is short circuited and the line X_1 is connected to the point B of the winding. For the second step the switch R_2 opens and R_1 closes. This connects the line X_1 to the point C, for the maximum boost. Such regulators are simple and reliable and enable normal voltage to be maintained on customers' circuits.

Other applications of tap changers under load range from an automatic voltage regulator designed to hold a constant voltage at a certain feed point up to complete tap-changing equipment for large power transformers.

CHAPTER VII

TRANSFORMER OIL AND ASKAREL

One of the most important of the factors which determine the life and the satisfactory operation of a transformer is the oil in which it is immersed. It is difficult to imagine large high-voltage transformers such as are in use today without oil or some equivalent insulating and cooling fluid, and oil is used in a large majority of transformers.

Characteristics of Transformer Oil. Some of the characteristics necessary or desirable in transformer oil are as follows:

1. High dielectric strength, to minimize clearances between coils and from winding to tank.
2. Freedom from acids, alkalies, and sulfur compounds, to prevent corrosion of the copper and injury to the insulation.
3. Low viscosity, to permit rapid circulation of the oil.
4. Low freezing point, to keep the oil liquid in cold weather.
5. High resistance to emulsion, to prevent holding water in suspension in the oil. A small trace of moisture decreases the dielectric strength of the oil greatly.
6. Freedom from formation of sludge under normal operating conditions.

Much time and money have been spent by manufacturers of transformers, in cooperation with the oil companies, to develop an oil having these desirable qualities, and transformers should be operated only in oil recommended by the manufacturer.

Maintenance of Oil. Having received the right oil, the operator's responsibility may be summarized in one sentence: "Keep it dry and clean." Good transformer oil when free from moisture should not break down in the standard test cup at less than 22,000 volts, and it may run considerably higher. The standard test cup is an oil container of insulating material having two flat parallel electrodes 1 inch in diameter and $\frac{1}{10}$ inch apart (see Fig. 73). The dielectric test is a very sensitive indicator of the dryness of transformer oil, since as little as 0.005 per cent of moisture in the oil will lower the breakdown voltage to about one-half that for dry oil.

Source of Moisture. Moisture may find its way into transformer oil in several ways. If the drums in which oil is shipped are exposed to rain, moisture may enter around the threads of the bung or through defective seams. The drums should therefore be stored in a dry place. Another source to which the presence of moisture in large transformers is sometimes attributed is *breathing*. When the transformer is loaded and becomes warm, both the oil and the air in the tank expand, and if there is a vent, a part of the air will be forced out. When the load is disconnected, the action is reversed and air is drawn into the transformer from the atmosphere. This air carries a certain amount of moisture, and a part of this moisture may be condensed inside the tank. Various means, described in another chapter, are used to prevent moisture from entering the oil because of breathing.

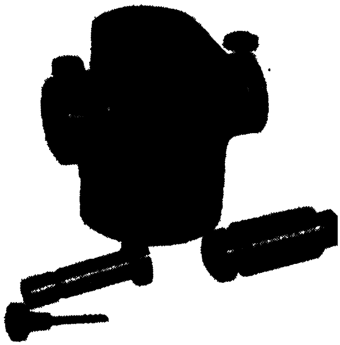


FIG. 73. Oil test cup.

Dirt and Sludge. Any foreign matter in the oil is evidently a source of possible danger, and oil is usually handled carefully enough to avoid external dirt. However, oils, when heated sufficiently in the presence of oxygen, will throw down a heavy precipitate, or sludge. This deposits on transformer coils and cooling surfaces and obstructs the oil ducts, thus increasing the temperature rise of the transformer. Modern oils are much better from the sludging standpoint than earlier oils, but they still must be watched, and high temperatures in the presence of oxygen must be avoided.

Handling Oil. When new oil is put into service, several precautions should be taken.

A drum of cold oil should not be opened in a warm room but should be allowed to stand until it reaches the room temperature to avoid *sweating.*

When the drum is opened, a sample of the oil should be tested before the drum is emptied.

The transformer tank which is to receive the oil must be clean and free from moisture. If sludged or carbonized oil has been removed from the tank, the transformer and the inside of the tank can be cleaned by washing with clean oil, under pressure if necessary, and wiping with clean, dry, lint-free cotton cloths.

New oil should be strained through several thicknesses of clean, dry, closely woven cotton cloth to remove any particles of scale which may have been loosened from the drum or tank car during shipment.

Always use metal hose—not rubber hose—for handling oil. The oil is easily contaminated by the sulfur in rubber.

Oil in transformers should be sampled and tested before the transformer is put into service.

Care also is necessary with oil which has seen service, for oil in transformers is liable to deterioration from moisture and from oxidation. Moisture may enter the tank through breathing or through leaky cooling coils or covers. Oxidation occurs to some extent whenever oil is in contact with air, but it becomes serious only when the temperature of the oil is high. Oxidation darkens the color of the oil and tends to increase its acidity, and it may cause the formation of sludge. Proper refining can produce an oil which will not sludge under normal operating conditions, but excessive temperatures, with oxygen, may cause sludge in any oil. Oil which has begun to sludge will continue even after it has gone through a filter press or centrifuge, because the fluid substances in process of changing to sludge are not removed by these devices.

The organic acids caused by oxidation of the oil are normally not dangerous, but if the process is continued long enough, they may become so strong as to damage the insulation.

Inspection of Oil. In view of the dependence of a transformer on the condition of its oil, and in view of the danger of contamination of oil, a periodic inspection and test of the oil in transformers in service is necessary. The interval between inspections depends on circumstances, such as the importance of the transformer and the load which it carries. The NELA has recommended that power-station apparatus be inspected at least once in three months and distribution transformers at least once a year. Inspection of oil in ordinary transformers should include the following:

Check of Oil Level. The proper oil level is marked either on the oil gage or on the tank wall.

Check of Dielectric Strength. Tests below 20 kilovolts in the standard test cup are undesirable, and if the test is as low as 18 kilovolts, the cause should be investigated and the oil brought back to normal before it is used further.

Check on Sludge. A visual examination will show if sludge is present. If sludge is found, the oil should be purified before it is used, and thereafter it should be carefully watched to see that it is purified again before sludge has reformed to a dangerous extent. Oil which has once sludged will sludge more quickly a second time.

Check on Resistance to Emulsion. This test indicates the ability of the oil to throw particles of moisture down to the bottom of the tank, where they are relatively harmless, rather than to hold them in suspension.

The American Society for Testing Materials has prepared complete specifications for making the required tests on oil, and for the sake of uniformity and completeness these specifications should be followed. For companies not equipped to make the tests it is convenient to send samples of the oil to one of the recognized testing laboratories.

Sampling Oil. The ASTM has also formulated rules for sampling oil, from which the following requirements are abstracted:

The sample container shall be a clear glass bottle of not less than 8-ounce capacity and shall be cleaned and dried. If the sample is to be tested for color or for sludge characteristics, it must be kept in the dark. This is not necessary for any other tests. Use a new cork—not a rubber stopper—for each sample.

The clean dry bottle shall be thoroughly rinsed with benzine or gasoline which has withstood a test of at least 25 kilovolts in a standard test cup and shall be allowed to drain. The bottle shall then be tightly corked, and the cork and the neck of the bottle shall be dipped in melted paraffin. It is preferable to heat the bottle and the cork for 1 hour at a temperature of 100°C after draining and to cork the bottle while hot.

Samples from oil drums can be taken by means of a *thief.* A recommended form is made of tin to the dimensions shown in Fig. 74. Another form is a plain glass tube 36 inches long.

Before a thief is used, it should be cleaned by rinsing in dry gasoline. When not in use it should be stored in a vertical position in a dry compartment at a temperature not less than 37.8°C (100°F). To take a sample, close the hole at the top of the thief with the thumb, and thrust the thief quickly to the bottom of the receptacle. Remove the thumb, and allow the thief to fill with oil. Replace the thumb over the top hole, withdraw the thief, and allow the oil to flow into the sampling receptacle. Do not close the lower hole with the free hand, and do not allow the oil to touch the hand while flowing into the sampling receptacle. When separate samples are to be taken from several drums, separate thiefs should be used or else the thief should be well drained and then washed with oil from the next drum to be sampled. The oil thus used for washing should be thrown away before taking the oil to be kept as a sample.

Oil samples from transformers in service can be taken from the drain plug or from the sampling valve provided for the purpose. Enough oil should be wasted to be sure that the sample represents the oil in the bottom of the tank, and not that which may have been standing in the sampling pipe. The same care should be taken to avoid contaminating the sample as when taking samples of new oil.

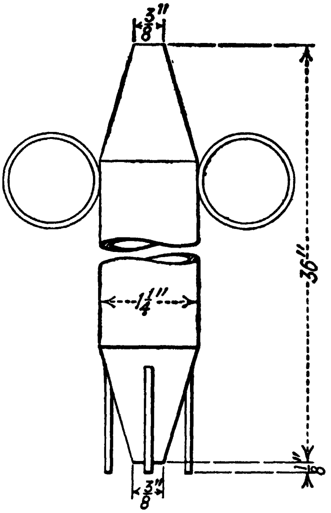


Fig. 74. Thief, for sampling oil.

Oil Treatment. When the oil sample from a transformer shows a dielectric test below 22 kilovolts, or when there is visible evidence of sludge or other impurities, the oil should be treated in a centrifuge or in a blotter filter press or both. A form of centrifuge which separates the water and other impurities by centrifugal force is shown in Fig. 75, and a filter press in Fig. 76. The action of the blotter filter press in separating the water depends on the fact that water will be retained in the blotters while oil passes through. It follows that this type of purifier alone is not suitable if large quantities of water are to be removed because of the frequent removal and drying of the blotters which would be necessary. In such a case it is better to use a centrifuge first, followed, if necessary, by the filter press.

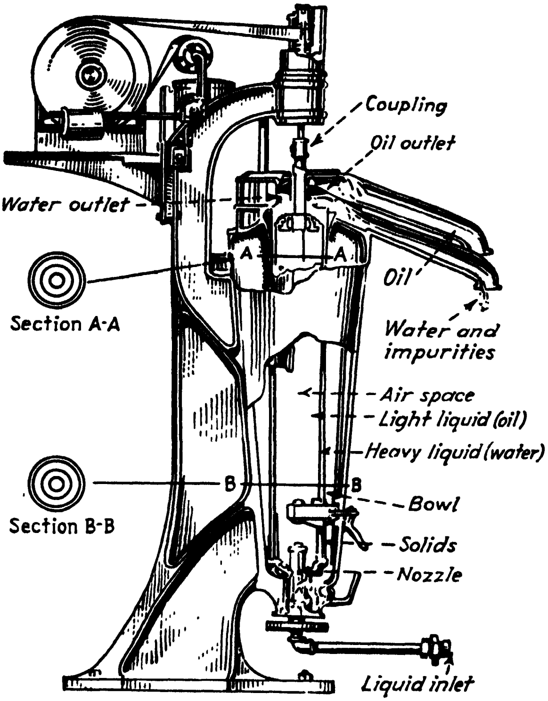


FIG. 75. Cross section of centrifuge.

The quickest method of purifying a quantity of oil is to run it through the purifier—centrifuge or filter press—into a clean, dry storage tank. If the filter press is used, the blotters must be changed before they become saturated. It is frequently desired, however, to treat the oil in a transformer while the transformer is in operation. This can be done by taking oil from the bottom of the tank, running it through the purifier, and returning it to the tank just below the oil level to prevent aeration of the oil. Most large transformers are provided with pipe connections and valves near the top and bottom to facilitate connection to the filter press. The filtering should be continued until a sample of the oil shows a satisfactory test.

Askarel. "Askarel is a synthetic nonflammable insulating liquid, which, when decomposed by the electric arc, evolves only nonexplosive gaseous mixtures."* It can be used where oil is prohibited because of possible fire hazard. It is almost 75 per cent heavier than oil and costs considerably more. A special treatment is required for transformers immersed in askarel, for it will attack many of the varnishes ordinarily used in transformer treatment. High-voltage transformers in askarel require more insulation than those in oil.

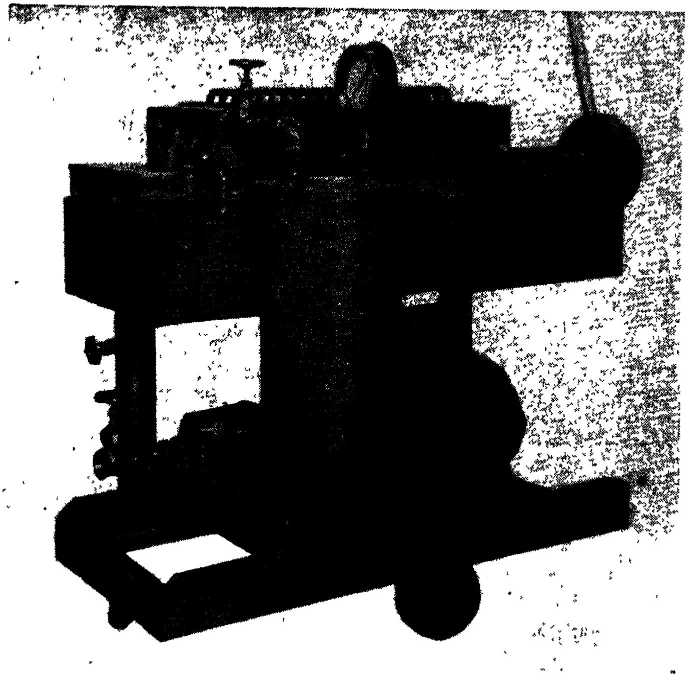


FIG. 76. Oil filter press.

In handling askarel the same precautions must be taken as in handling oil to keep it clean and dry. Special care should be taken to avoid contamination of the askarel with oil. The two liquids are perfectly miscible, and there is no practical way to separate them. Long contact of askarel with the skin sometimes causes irritation and should therefore be avoided.

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* American Standards definition.

The reconditioning of askarel is accomplished by mixing it with activated clay and then running it through a filter press. On account of the high specific gravity of askarel, water and most other impurities will rise to the top. The reconditioning apparatus therefore should be connected to draw the askarel from the top of the tank and return it at the bottom.

CHAPTER VIII

MAINTAINING OIL QUALITY

Since the satisfactory operation of transformers depends so largely on the condition of the oil, devices and methods for keeping the oil clean and dry are of prime importance. Designers have given much attention to this subject. For a number of years it was the practice to build small distribution transformers with a felt gasket between the tank and cover. This allowed a certain amount of breathing, but at the same time it kept out dirt and most of the moisture. Thousands of transformers were built in this way, and many of them are still in satisfactory operation. The present tendency is to seal the cover tightly so that the transformer can be shipped with oil in the tank. No provision is made for breathing.

Open-air Breathers. Larger transformers, especially those for the lower voltages, are sometimes provided with open-air breathers. These are simply vents to the atmosphere, screened to prevent the entrance of insects and made with an opening pointing downward so that rain cannot enter. These prevent building up a pressure inside the tank as the oil expands but do not protect the quality of the oil.

Dehydrating Breathers. If a breather is to be used, it is generally better to use a dehydrating breather, which permits breathing but removes the moisture from air entering the tank. Figure 77 shows one form of dehydrating breather. The chamber *A* contains the dehydrating material, which may be either silica gel impregnated with cobalt chloride or activated alumina. These materials are blue when dry and a whitish pink when damp. The color can be observed through two glass windows in the front of the container.

A small pipe from the gas space above the oil in the transformer connects to the breather at *C*. The breathing regulator, shown enlarged at the left, is connected to the bottom of the chamber *A*. It consists of two concentric tubes opening together at the bottom but separated at the top. The tubes are filled with Prestone to the height of the plug *D*. As the pressure inside the transformer rises, the Prestone is forced downward in the inner tube. If the bottom of the inner tube is uncovered, air will bubble up through the Prestone in the outer tube and escape through the vent in the plug *E*. Similarly, if the pressure inside the transformer tank falls below atmospheric pressure, the Prestone will be drawn up into the inner tube. When the bottom of this tube is uncovered, air can enter through *E*, bubble up through the Prestone, pass through the dehydrating material and so into the transformer tank. The Prestone acts as a seal which will not discharge or admit air until the difference between atmospheric pressure and the pressure inside the transformer tank reaches approximately 1 pound per square inch. This eliminates breathing for small changes in pressure and materially reduces the amount of oxygen which would otherwise be drawn into the tank.

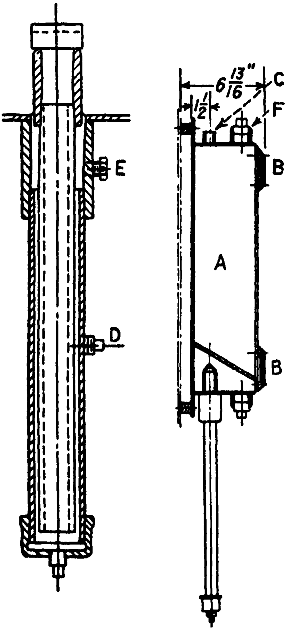


Fig. 77. Dehydrating breather.

When the whitish pink color begins to be visible through the upper window, the moist material can be removed through the lower window and a fresh charge of dry dehydrating material can be put into the container through the plug *F*. The material which has been removed can be dried and used again.

Such a dehydrating breather is very satisfactory for high-voltage instrument transformers and other transformers in which the oil is not likely to reach a high temperature. It effectively excludes moisture, and although it does not exclude oxygen, the oxygen does little damage to modern transformer oil at low temperatures.

Other Protective Schemes. Breathers alone are not sufficient protection for large and important power transformers. Such transformers are liable to occasional overloads which may over-heat the oil and cause a tendency to sludge if oxygen is present. Rarely, but sometimes, such transformers also suffer a short circuit which vaporizes a part of the oil, and cases are on record where the oil gas, mixing with the air above the oil, has formed an explosive mixture which ignited from the arc and did considerable damage. For both these reasons it is worth while to guard against oxygen in contact with the oil as well as against moisture. Two chief methods have been developed for this purpose, expansion tanks, or *conservators*, and *inertaire* apparatus.

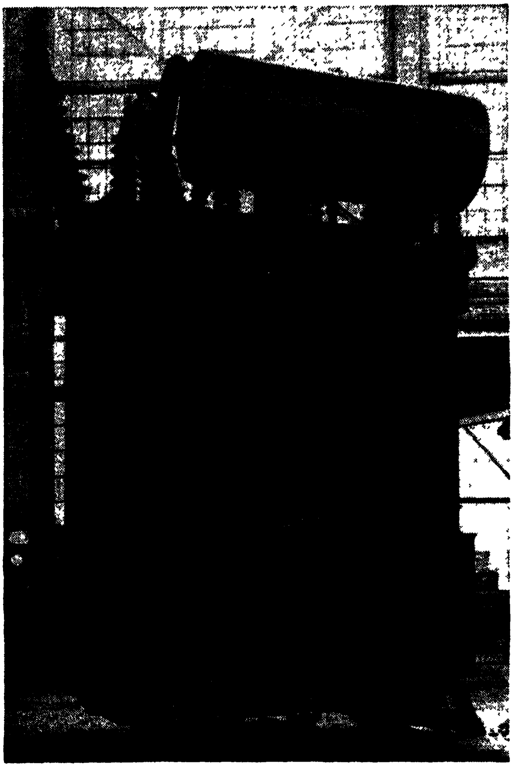


Fig. 78. Transformer with expansion tank and relief diaphragm.

Expansion Tanks, or Conservators. The expansion tank is a small tank mounted above the cover of the main transformer tank and connected to the oil space of the main tank by a relatively small pipe. The oil level is set so that the main tank is entirely filled with oil and the expansion tank is about half full, and the interior of the expansion tank above the oil level is connected to the atmosphere through a dehydrating breather. The only interchange of oil between the main tank and the expansion tank is that caused by expansion and contraction as the temperature changes and is therefore slow. In the expansion tank, then, dry air is in contact with a comparatively small surface of relatively cool oil, which is a great improvement over the ordinary tank with air space above the oil.

To guard against the possibility of a sudden high pressure caused by a breakdown or a short circuit in the transformer winding, a diaphragm relief device is provided. This consists of a large opening to the atmosphere covered by a diaphragm which keeps out dirt and moisture but which can easily be burst by pressure inside the tank. The relief device must be above the level of the oil in the expansion tank to prevent an overflow of oil in case the device operates. A usual arrangement is shown in Fig. 78.

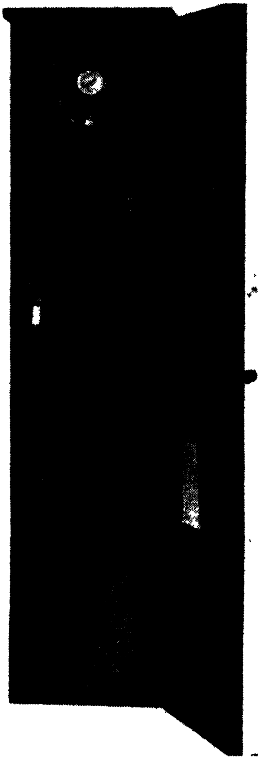


FIG. 79. Inertaire apparatus with nitrogen tank.

Inertaire Apparatus. The inertaire apparatus is used with transformers mounted in airtight tanks without expansion tanks. The space above the oil, however, is filled with an inert gas, usually nitrogen, and a breather is arranged so that, when the transformer breathes inward, it draws in dry nitrogen instead of air.

In the early form of inertaire apparatus the dry nitrogen was obtained by drawing atmospheric air through jars of chemicals which absorbed the moisture and the oxygen. The later arrangement uses a cylinder of compressed nitrogen with a reducing valve, as shown in Fig. 79. When the pressure in the transformer tank falls to 4 pounds per square inch below atmospheric pressure, a breathing regulator allows nitrogen to flow through the reducing valve into the transformer tank. If the pressure in the tank rises to 8 pounds per square inch above atmosphere, the breathing regulator discharges the excess into the atmosphere. This range of pressure is sufficient to cover most of the changes during normal operation, and the nitrogen in the cylinder is therefore used only slowly.

Pressure-relief Device. With the inertaire apparatus a device is necessary to relieve the pressure in the tank in case of an arc or short circuit under the oil. For many years the diaphragm pressure-relief valve shown in Fig. 80 has been used. It takes the place of the manhole cover in an ordinary transformer. Under normal conditions the diaphragm, which is clamped tightly against a gasket as shown, forms an airtight cover over the large opening. The diaphragm is protected on the outside by an auxiliary cover which sits on a gasket and forms a secondary seal between the outside and the inside of the transformer. The motion of the auxiliary cover away from its seat is limited by the springs on the bolts shown below the cover. If a short circuit in the transformer should cause a pressure great enough to burst the diaphragm, the auxiliary cover would be lifted, making a large annular opening for the escape of the gases. With the relief of the internal pressure the auxiliary cover would return to its seat on the gasket and keep the nitrogen in the tank and the dirt and moisture out.

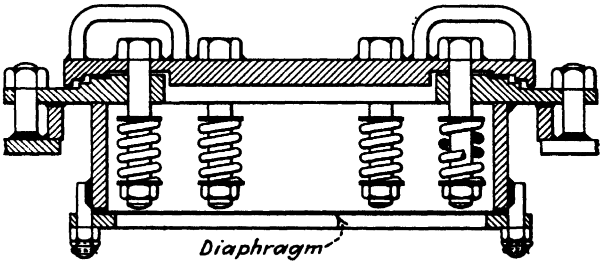


FIG. 80. Diaphragm pressure-relief valve.

More recently a mechanical relief device, shown in Fig. 81, has been developed. The device is shown in its normal position. Any pressure inside the tank tends to expand the tripping bellows and thus to raise the trigger. This tendency is resisted by the pressure of the spring in the toggle. If the gas pressure in the tank becomes great enough to overcome the spring, the trigger is snapped upward by the combined action of the tripping bellows and the toggle spring. The nut on the bottom of the trigger strikes the latch plate, which releases the latches and permits the relief cover to rise. This provides a large opening for relief of the pressure. After the excess gases have been discharged, gravity returns the relief cover to its normal position and thus prevents the entrance of dirt or moisture. To reset the mechanism after it has operated, the device must be removed from the tank.

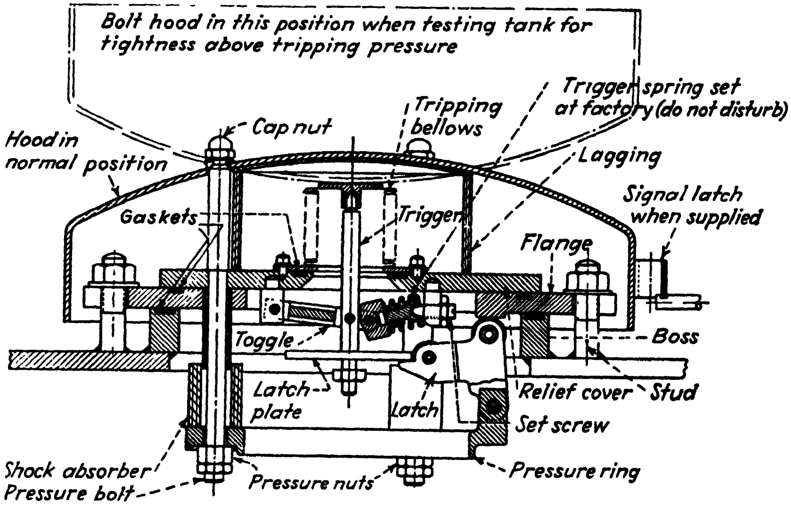


FIG. 81. Mechanical relief device.

The inertaire apparatus thus protects the transformer during normal operation by keeping the oil free from moisture and oxygen, and it protects the transformer during abnormal conditions by (1) preventing a gas explosion, (2) providing a body of nitrogen which acts as a cushion for the first shock of pressure caused by a short circuit, and (3) relieving the excess pressure to the atmosphere and resealing the tank. Another incidental advantage is that frequent inspections of the oil are unnecessary, since it is almost impossible for the oil to become contaminated as long as the supply of nitrogen is adequate.

From these various protective schemes it is possible to choose one suitable for any transformer and for any operating conditions. The right protection, plus a suitable inspection schedule to ensure that the protection remains effective, will assure the maximum of satisfactory service from the transformer.

CHAPTER IX

MECHANICAL FORCES IN TRANSFORMERS

When current is flowing in a wire, the wire is surrounded by a magnetic field. This field is usually pictured as composed of circular lines of force surrounding the wire, as shown in Fig. 82. If the current is flowing away from the observer, *i.e.*, down into the paper in Fig. 82, the direction of the flux is clockwise around the wire. If the current is toward the observer, the direction of the flux is counterclockwise. A good way to remember this relation is the right-hand-screw rule. If a right-hand screw moves in the direction in which the current flows, the rotation of the screw corresponds to the direction of the lines of force.

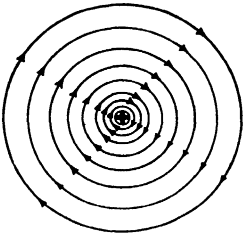


FIG. 82. Magnetic field around a wire carrying current.

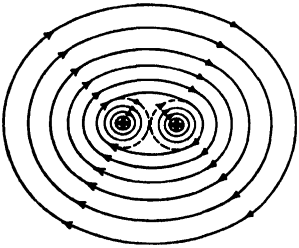


FIG. 83. Distortion of magnetic field around two wires carrying current in the same direction.

Mechanical Force. The action of the lines of force is analogous to that of rubber bands. If two wires carrying current in the same direction are near together, the lines of force from one, in the space between the two wires, will cancel the lines of force from the other, and the resultant field will encircle both wires, as in Fig. 83, and tend to draw them together. If the currents are in opposite directions, the fields are distorted and crowded in the space between the two wires, as in Fig. 84, and the tendency is to force the wires apart.

In a coil of many turns these forces are multiplied, and one of the problems of design is to provide means for supporting the forces thus caused.

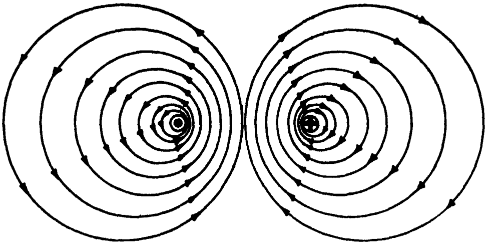


FIG. 84. Distortion of magnetic field around two wires carrying current in opposite directions.

Forces in Transformers. In transformers all coils which carry current in the same direction attract one another and coils which carry current in opposite directions repel one another. In other words, all primary coils attract one another; likewise all secondary coils. But primary coils repel secondary coils, and vice versa. These effects always exist when the transformer is operating, but under normal conditions the forces are relatively small. In case of short circuit, however, these forces may become great enough to wreck the transformer if the coils are not adequately supported.

Supporting the Coils. The method of support depends on the coil arrangement. Figure 85 shows a cross section of parallel interleaved coils in an iron opening. The current in the low-voltage coils is assumed to be downward into the paper, as shown, and that in the high-voltage coils up out of the paper. The magnetic flux then will be distributed as indicated, pulling like coils together and pushing the low-voltage coils away from the high-voltage coils.

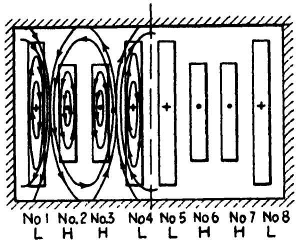


FIG. 85. Magnetic field in part of transformer with pancake coils.

If the coils are symmetrically arranged as in Fig. 85, the forces within the transformer will be balanced, except the forces acting on the two end coils. The figure shows a transformer composed of four groups, each group containing one low-voltage coil and one high-voltage coil, with the same number of ampere turns in each coil. Such an arrangement is a *four high-low*, or *four H-L*, grouping. In each group there is repulsion between the two coils, but between groups is an attraction. Thus coil 2 is repelled by coil 1 and attracted by coil 3, while coil 3 is attracted by coil 2 and repelled by coil 4. The total force thus tending to bring coils 2 and 3 together is resisted by the compression of the material between them—insulation or duct spacers as the case may be. Similar conditions exist for coils 4 and 5 and for coils 6 and 7.

The repulsion between the coils in each group is balanced by the repulsion in adjacent groups, finally appearing as pressure against the end coils of the transformer. This pressure on the end coils is evidently that corresponding to the pressure of one group, not the sum of the pressures, and its maximum will depend on the number of turns in the end coils and on the short-circuit current of the transformer. The short-circuit current, in turn, depends on the reactance of the transformer, which varies with the number of H-L groups. As a result of these relations it can be shown that the total pressure on the end coils, under conditions of short circuit, varies but little with the coil grouping for a given design.

On the other hand, a small number of H-L groups usually corresponds to a high reactance. This causes a high regulation, especially with loads of low power factor, and it tends to cause a high copper loss because of higher eddy-current losses in the winding. The transformer is usually designed to give the desired reactance, and the mechanical force against the end coils is supported by suitable coil bracing.

Coil Bracing. For large transformers the interleaved coils are often made rectangular in shape and built into a shell-form core. With this construction the core itself furnishes sufficient bracing for the part of the coils within the iron. The coil ends which project beyond the iron need additional bracing, and this is easily provided by reinforcing plates, one at each side of the coil stack, held together by tie rods, as in Fig. 86. In form-fit tanks the reinforced tank wall takes the coil thrust through blocking placed between the coil ends and the wall.

If the electrical centers of adjacent coils are not exactly opposite each other owing, for instance, to manufacturing variations, the force between the coils may be resolved into two components,

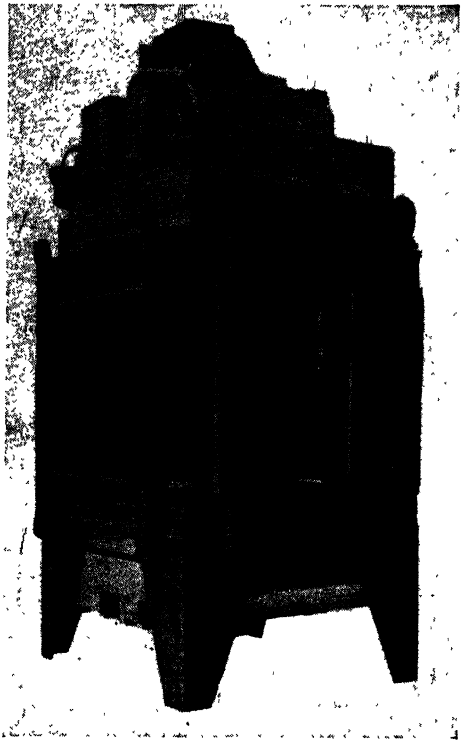


FIG. 86. Large shell-form transformer showing bracing of coil ends.

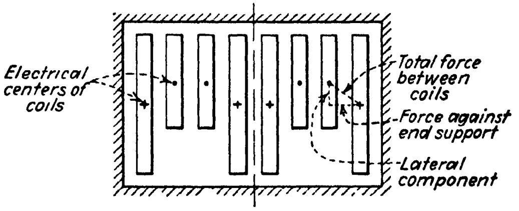

Electrical centers of coils
Total force between coils
Force against end support
Lateral component

FIG. 87. Mechanical forces with unsymmetrical coils.

one pushing the coils directly apart and the other tending to shift the coils laterally, as indicated in Fig. 87. Provision must be made in the design to support this lateral force as well as the direct force against the end supports.

Besides the parallel interleaved arrangement of coils, another arrangement is the concentric, in which the coils are cylindrical in form—either circular or rectangular—and the high-voltage and the low-voltage coils are placed one inside the other. For small transformers the coils are often wound on rectangular molds. Figure 88 shows transformers made with such coils. In large transformers the concentric coils are generally wound on circular molds and appear as in Fig. 89.

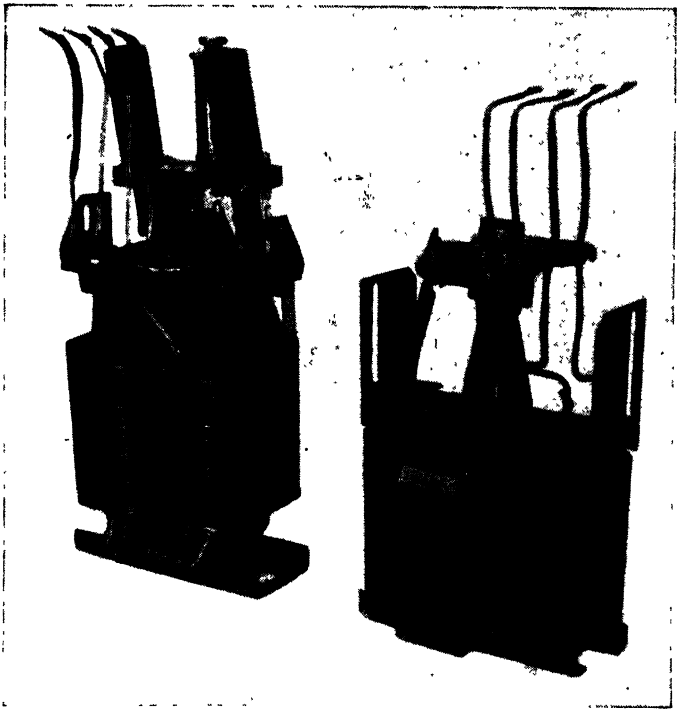


FIG. 88. Small transformer with concentric coils.

In transformers with concentric coils the force between the primary and secondary windings is radial. This force tends to make the outer coil assume a circular shape and then tends to stretch the wire so as to increase the diameter of the coil. At the same time the radial force tends to crush the inner coil against the core. Fortunately, it is easy to brace the inner coil against the core so that it cannot be crushed, and the tensile strength of the wire in the outer coil is ample to stand the stress which can be applied to it. This form of construction would be ideal from the standpoint of security against distortion by short circuits if perfect accuracy in building and assembly could be assured. But if one coil is displaced axially from its correct position by even a small amount, a large axial force may result. This is illustrated in Fig. 90, which is a cross section through a transformer with two concentric circular windings. If the electrical centers of the two coils were exactly opposite, *i.e.*, in the same plane, the force between the two coils would be purely radial, but if one coil is shifted, as shown, an axial component is introduced. In the triangle of forces in the figure the hypotenuse is the total force between coils

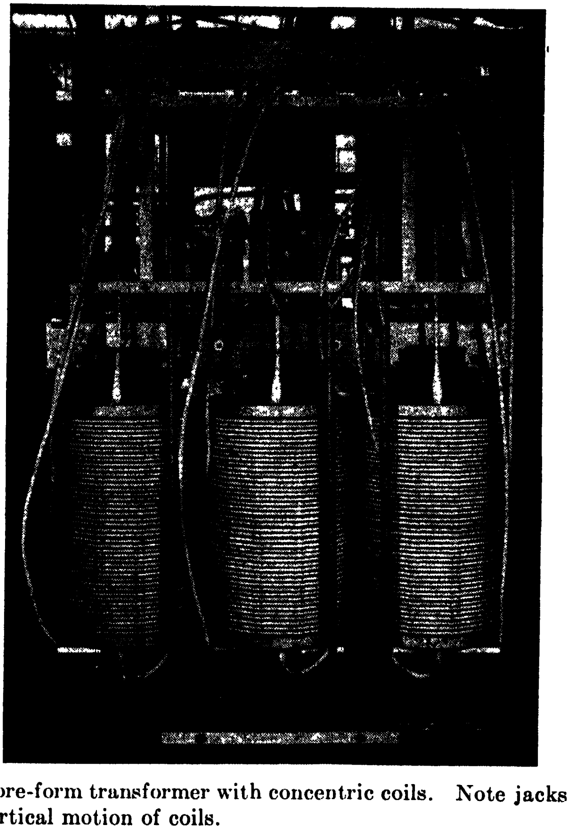


FIG. 89. Core-form transformer with concentric coils. Note jackscrews to prevent vertical motion of coils.

and the other two sides are the radial and axial forces, respectively. The axial force, or end thrust, may become large under short-circuit conditions, and the coils must be designed and braced to withstand it.

As an example of the magnitude of the forces which may be expected, a certain 2,500-kva 44,000-volt shell-form transformer with 6 per cent reactance requires bracing on the end coils to withstand an average force of 27,000 pounds during short circuit. A core-form transformer of similar rating with 6 per cent reactance will have an end thrust of 18,000 pounds per leg if the electrical centers of the coils are displaced ½ inch. In larger transformers these forces are correspondingly larger.

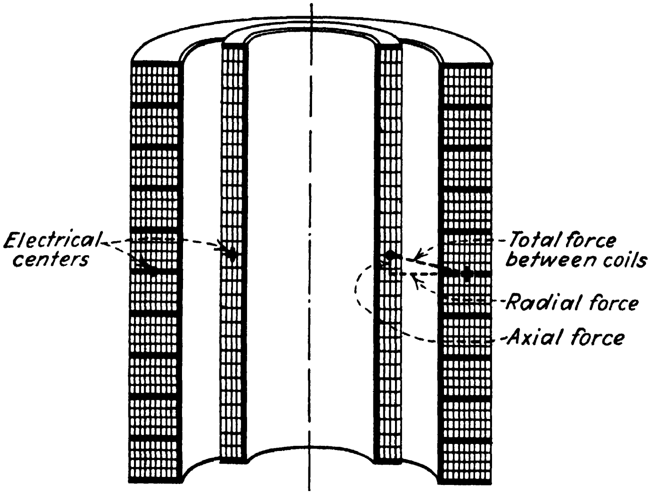


FIG. 90. Axial and radial forces on concentric coils.

The question of suitable mechanical construction and adequate coil support is thus as important as any other question of design.

CHAPTER X

TRANSFORMER INSULATION AND LIGHTNING PROTECTION

Within the last few years much has been learned about insulation, especially with regard to its ability to withstand surges, or abrupt high-voltage impulses of extremely short duration, such as those which result from lightning. As a result it is now possible to design transformers which are practically immune from damage by lightning and thus to eliminate a chief source of trouble.

Origin and Effect of Surges. Surges are sometimes caused by switching or by arcing grounds, but the surges which do the most damage are those caused by lightning. They may be the result of a direct stroke on the line or of a stroke in the vicinity. When such a stroke occurs, the potential of the adjacent line is raised instantaneously far higher than its normal voltage above ground, and the charge thus produced travels along the line as a high-voltage impulse. If it reaches a transformer protected by lightning arresters, the impulse, if high enough, will "spill over" the lightning arrester to ground, impressing on the transformer only the part of the wave which occurred before the spill over. If the impulse wave is not high enough to discharge the arrester, the full wave will be impressed on the transformer. What happens next will depend on the design of the transformer. If the insulation from coils to ground, from coil to coil, and from turn to turn is strong enough to withstand the voltages produced by the impulse at these points, the transformer will not be damaged. Actually, transformers, even those built a number of years ago, have shown a good record of life and reliability. The time and money which have been spent in the investigation of insulation and of lightning have been for the purpose of eliminating a small percentage of failures. They have resulted also in superseding "brute strength" insulation by a more scientific method of insulation design, in which the distribution of stress can be controlled and the insulation can be placed where it is needed. This produces a stronger transformer with less material.

SURGE-PROTECTED TRANSFORMERS

The modern method of avoiding lightning trouble in transformers is to design the transformer insulation so that each part of it is strong enough to withstand the maximum stress which can be put upon it by a specified impulse-voltage wave. A protective device is then provided to discharge to ground any voltage which may appear on the line higher than the specified impulse. For several years a coordinating gap was recommended as the protective device and standard gaps were proposed for the various voltage classes. Figure 91 is a schematic sketch of a transformer with a coordinating gap.

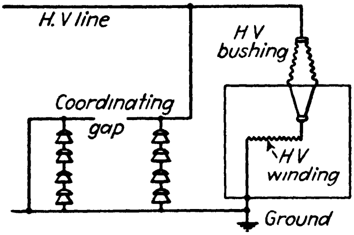


FIG. 91. Schematic sketch of a transformer with coordinating gap.

The impulse strength of such a transformer was stated in terms of its test gap. For reasons given later, however, this method of stating impulse strength has been superseded by a statement of the peak voltage of a standard impulse wave which the transformer is designed to stand.

To make the insulation adequate the designer usually tries (1) to get, as nearly as practicable, a uniform distribution of the impulse voltage through the winding and thus avoid piling up a high voltage across a few end turns, (2) to make the internal insulation of the transformer stronger than the bushing and thus ensure that, if a breakdown should occur, if would be outside the tank, where comparatively little damage would be done, (3) to ensure that any failure of the bushing will be by flashover, and not by puncture, and (4) finally to make the weakest point in the transformer stronger, by an adequate margin, than the protective device.

Uniform Impulse Distribution. A lightning impulse is of extremely short duration. The standard impulse test wave, which is intended to be typical of lightning impulses, rises to its crest in about 1½ microseconds (0.0000015 second) and falls again to half its maximum in about 40 microseconds. For such waves the initial distribution of voltage through the winding depends only on the electrostatic capacity between the various parts of the transformer. Uniform distribution can be approximated by making the capacity between the high-voltage coils large and uniform and by making the capacity from the high-voltage coils to the low-voltage winding and to ground comparatively small. As a help in getting the impulse through the winding and to prevent voltage from piling up on the end turns, static plates are sometimes used. They are placed adjacent to the end coils but are thoroughly insulated from the face of the coils. The insulated plate is connected to the coil lead as shown in Fig. 92. The static plate thus forms the first plate of a condenser whose other plates are the coils of the winding and the static plate at the other end of the coil stack. The fact that the various plates are connected together metallically makes little or no difference in the initial distribution of the voltage.

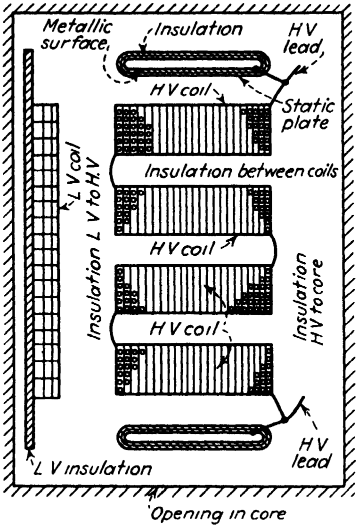


FIG. 92. Section of transformer coils showing static plates.

Uniform impulse distribution not only prevents piling up a high voltage at the end of the winding, thus removing the necessity of extra insulation of the end turns, but also removes the probability of dangerous oscillations in the winding, which might otherwise add to the stress in the insulation.

Strength of Major Insulation. The major insulation of power transformers usually consists of a series of ducts filled with oil and separated by fibrous material such as pressboard, micarta, or similar material in the form of barriers. In the study of such insulation it has been found that an impulse can follow a *creepage* path along the surface of such barriers for considerable distances with comparative ease whereas the same insulation placed perpendicular to the direction of the stress is much more effective. The major insulation, therefore, can be much strengthened without increasing the dimensions if creepage surfaces are eliminated and if the barriers are arranged so as to check the initial discharge which begins a breakdown.

Strength of Bushings. The dielectric strength of high-voltage bushings is known quite definitely, and it is common practice to apply a flashover gap to the outside of bushings so as to ensure that the bushing will flash over before either the transformer or the bushing will puncture.

Coordinated Insulation. The term *coordinated insulation* is sometimes applied to the arrangement just described where the transformer is stronger against impulses than the bushings and the bushings are stronger than the protective device. That such coordination is effective the record shows. Transformers insulated in this way have been built since 1931 and have an excellent record of reliability.

Sufficient information has now been accumulated so that transformers can be designed with assurance that they will have the desired impulse strength, and impulse tests are sometimes included in the regular test schedule.

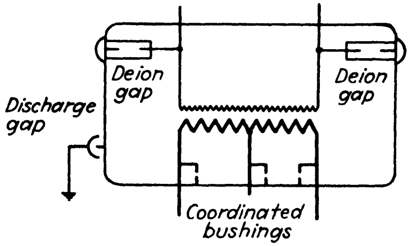


FIG. 93. Impulse-protected distribution transformer.

Impulse Protection of Small Distribution Transformers. Small distribution transformers are usually installed on poles, and the conventional method is to connect a fuse in each high-voltage line and a lightning arrester from each high-voltage line to ground and to ground the low-voltage neutral. With this arrangement, outages caused by lightning are not infrequent, especially in exposed locations. Sometimes the transformer is damaged, and sometimes the fuse is blown, but in either case a service interruption occurs.

To remedy this condition transformers have been built with deion gaps connected between the high-voltage lines and the case, with the low-voltage bushings coordinated with the insulation of the winding as to flashover strength and with a relief gap between the tank and ground, as shown in Fig. 93. The deion gap limits the voltage which can exist between the high-voltage winding and the tank, the low-voltage bushings limit the voltage which can exist between the low-voltage winding and the tank, the two together limit the voltage which can exist between the high-voltage and the low-voltage windings, and the relief gap limits the voltage between tank and ground. All these limits are well below the impulse strength of the corresponding parts of the transformer, and the insulation is thus protected in all directions.

The deion gap is a spark gap designed to flash over if the voltage across it exceeds a predetermined value. When an ordinary spark gap flashes over, the air in the discharge path is ionized and becomes a conductor and power current is likely to follow. To prevent this the deion gap is provided with a number of small openings between fiber plates. If power current follows a discharge, the heat produces a vapor from the fiber which deionizes the path and thus interrupts the power current at the first zero. A resistance is used in series with the gap to limit the power current to a value which the device can interrupt.

The latest developments in distribution transformers have added a number of refinements designed to protect the transformer not only from lightning but also from long-continued overloads and from short circuits.

STANDARD INSULATION TESTS

For many years the insulation of transformers has been tested by applying between each winding and ground a voltage considerably higher than the normal voltage of the winding. This shows the strength of the insulation at normal frequencies but does not give sufficient information about its strength against impulses.

Impulse Tests. The method of specifying and testing the impulse strength of insulation was developed over a considerable period of time by the labors of many workers in this field. From time to time the Transformer Subcommittee of the American Institute of Electrical Engineers issued recommendations on the subject which embodied the latest developments. At length, a committee of the American Standards Association, including representatives of the American Institute of Electrical Engineers, The National Electrical Manufacturers Association, the Electric Light and Power Group, the Association of American Railways, and the National Bureau of Standards, prepared a set of American Standards for Transformers, etc., which was issued in 1942. These

TABLE 11.030
Standard Dielectric Tests for Transformers,* Regulators, and Reactors

Insulation Class (a)	Rated Voltage between Terminals (b) (c)			Dielectric Tests									
				Low-Frequency Tests				Impulse Tests (h)					
	Distribution and Power Transformers, Regulating Transformers (a) Constant-Current Transformers (d) Step-Voltage Regulators (a) Induction-Voltage Regulators (a) Shunt Reactors, Potential Transformers			Oil-Immersed Type	Dry Type	Current-Limiting Reactors, Air Core		Oil-Immersed Type			Oil-Immersed Type		
				Distribution and Power Transformers, Regulating Transformers, Constant-Current Transformers, Step-Voltage Regulators, Induction-Voltage Regulators, Shunt Reactors, Instrument Transformers	Distribution and Power Transformers, Regulating Transformers, Constant-Current Transformers, Step-Voltage Regulators, Induction-Voltage Regulators, Shunt Reactors, Air-Blast Transformers			Transformers 500 Kva and Below, Constant-Current Transformers, Step-Voltage Regulators, Induction-Voltage Regulators, Instrument Transformers(i)			Transformers above 500 Kva, Regulating Transformers, Current-Limiting Reactors, Shunt Reactors		
	Single-Phase		Three-Phase			Oil-Immersed Type	Dry Type	Dry and Compound-Filled Types Instrument Transformers					
	For Y-Connection on 3-Phase System (e)	For Δ-Connection on 3-Phase System	Δ- or Y-Connected (e)	Dry and Compound-Filled Types Instrument Transformers				Chopped Wave		Full Wave	Chopped Wave		Full Wave
									Min Time to Flashover			Min Time to Flashover	
COL 1	COL 2	COL 3	COL 4	COL 5	COL 6	COL 7	COL 8	COL 9	COL 10	COL 11	COL 12	COL 13	COL 14
Kv	Kv Rms	Kv Rms	Kv Rms	Kv Rms	Kv Rms	Kv Rms	Kv Rms	Kv Crest	μ second	Kv Crest	Kv Crest	μ second	Kv Crest
1.2	0 to 0.69	0 to 0.69(f)	0 to 1.2	10(g)	4	12	12	36	1.0	30	54	1.5	45
2.5	....	....	2.5	15	10	17	25	54	1.25	45	69	1.5	60
5.0	2.89	2.89(f)	5.0	19	12	21	30	69	1.5	60	88	1.6	75
8.66	5.0	5.0 (f)	8.66	26	19	29	40	88	1.6	75	110	1.8	95
15	8.66	15	15	34	31	36	60	110(i)	1.8(i)	95(i)	130	2.0	110
25	14.4	25	25	50	..	60	85	175	3.0	150	175	3.0	150
34.5	19.9	34.5	34.5	70	..	80	115	230	3.0	200	230	3.0	200
46	26.6	46	46	95	..	105	..	290	3.0	250	290	3.0	250
69	39.8	69	69	140	..	160	..	400	3.0	350	400	3.0	350
92	53.1	92	92	185	..	210	..	520	3.0	450	520	3.0	450
115	66.4	115	115	230	..	260	..	630	3.0	550	630	3.0	550
138	79.7	138	138	275	..	310	..	750	3.0	650	750	3.0	650
161	93	161	161	325	..	365	..	865	3.0	750	865	3.0	750
196	113	196	196	395	..	425	..	1035	3.0	900	1035	3.0	900
230	133	230	230	460	..	485	..	1210	3.0	1050	1210	3.0	1050
287	166	287	287	575	..	590	..	1500	3.0	1300	1500	3.0	1300
345	199	345	345	690	..	690	..	1785	3.0	1550	1785	3.0	1550

Notes

* For test values for specialty transformers see 17 061

(a) For series windings in apparatus such as regulating transformers step and induction voltage regulators, reactors and current transformers the test values to ground shall be determined by the insulation class (Col 1) of the series windings rather than by the rated voltage between terminals

(b) Intermediate voltage ratings are placed in the next higher insulation class unless otherwise specified

(c) See 11 032 for regulating taps

(d) For additional voltage classes of constant current transformers see Table 14 048

(e) Y connected apparatus for operation with neutral solidly grounded or grounded through an impedance may have reduced insulation at the neutral as specified in 12 031

(f) Single phase distribution and power transformers, regulating transformers, oil immersed constant current transformers, step and induction voltage regulators for voltage ratings of 8 66 kv and below are insulated for the test voltages corresponding to the Y connection, so that a single line of apparatus serves for the Y and delta applications The test voltages for such delta-connected single phase apparatus are, therefore one step higher than needed for their voltage rating This rule applies also to some potential transformers as specified in Table 13 016

(g) The low frequency test value for induction voltage regulators is 4 kv The low frequency test value for secondaries of instrument transformers is 2 5 kv

(h) Standard impulse tests have not been established for (1) Low voltage windings of transformers for furnaces synchronous converters, and rectifiers, (2) Secondary windings of instrument transformers, (3) Dry type apparatus except primary windings of instrument transformers

Present day values for impulse tests of dry type distribution and power transformers are as follows

1 2 kv class 10 kv, 2 5 kv class, 20 kv, 5 0 kv class, 25 kv, 8 66 kv class 35 kv 15 kv class 50 kv These values apply to both chopped wave and full wave tests

(i) Instrument transformers are available in the 15-kv insulation class having a full wave impulse test value of 110 kv and a chopped wave impulse test value of 130 kv with minimum time to flash over of 2 microseconds

Standards were revised and reissued in 1948. They include a list of standard insulation classes and specify the test to be applied for each. The following paragraphs are quoted from the American Standards of 1948. The quotation is necessarily brief. For full information reference should be made to the complete Standards.

Insulation Classes and Dielectric Tests

11.030 Insulation-Class Designation

a. Apparatus covered by these standards shall be assigned insulation-class designations to indicate the dielectric tests which the apparatus is capable of withstanding.

b. Insulation classes shall be limited to those given in Table 11.030. Each section of these standards contains a similar table for apparatus covered by that section.

c. Apparatus designed for Y connection only, with neutral brought out through a bushing, shall be assigned insulation classes for both line and neutral terminals. The neutral may have a lower insulation class than the line (see 11.031).

11.031 Insulation Class of Transformer Neutrals. The minimum insulation class of the neutrals of transformers and other induction apparatus covered by these standards shall be as shown in Table 11.031 and as qualified below unless otherwise specified by purchaser or manufacturer. The following requirements are based on the assumption that the transformer neutral will, when necessary, be impulse protected.

a. Transformers designed for star connection only, with the neutral brought out and solidly grounded directly or through a current transformer, shall have a minimum insulation class at the neutral in accordance with Column 2, Table 11.031.

b. Transformers designed for star connection only, with the neutral brought out and connected to ground through the series winding of a regulating transformer, shall have a minimum insulation class at the neutral as determined from the maximum raise or lower phase to neutral voltage of the regulating transformer but shall be not less than specified in Column 3, Table 11.031. The same insulation class shall apply to the series winding of the regulating transformer. If the neutral of the regulating transformer is brought out, its minimum insulation class shall be in accordance with Column 2, Table 11.031.

c. Transformers designed for star connection only, with the neutral brought out and connected to ground through the series winding of a regulating transformer and a separate neutral impedance, shall have an insulation class at the neutral as determined from the addition of the maximum raise or lower phase-to-neutral voltage of the regulating transformer to the maximum low-frequency voltage across the separate neutral impedance but shall be not less than as specified in Column 3, Table 11.031. The same insulation class shall apply to the series winding of the regulating transformer. If the neutral of the regulating transformer is brought out, its minimum insulation class shall be determined by the maximum low-frequency voltage across the neutral impedance but shall be not less than as specified in Column 2, Table 11.031.

d. Transformers designed for star connection only, with the neutral brought out and connected to ground through a ground fault neutralizer or neutral brought out and isolated but impulse protected, shall have a minimum insulation class at the neutral in accordance with Column 4, Table 11.031.

Table 11.031

Minimum Insulation Class At Neutral

Winding Insulation Class at Line End	Minimum Insulation Class		
	Grounded Solidly or through Current Transformer *	Grounded through Regulating Transformer	Grounded through Fault Neutralizer or Isolated but Impulse Protected
COL 1	COL 2	COL 3	COL 4
Kv	Kv	Kv	Kv
1.2	Same as line end	Same as line end	Same as line end
2.5			
5.0			
8.66			
15	8.66	8.66	8.66
25	8.66	8.66	15
34.5	8.66	8.66	25
46	15	15	34.5
69	15	15	46
92	15	25	69
115	15	25	69
138	15	34.5	92
161	15	34.5	92
196	15	46	115
230	15	46	138
287	15	69	161
345	15	69	196

* For transformers 500 kva and below, a ground stud may be furnished unless otherwise specified.

e. When the insulation class of the neutral end of the winding differs from the insulation class of the highest voltage neutral bushing for which provision is made in the transformer tank, the insulation class of the neutral on which impulse tests are based shall be whichever is lower: the winding insulation class or the bushing insulation class.

11.032 Regulating Taps. Transformers may be provided with taps for voltages above the values in Columns 2, 3, and 4 of Table 11.030, without increasing the insulation class. For transformers rated 500 kva and below, these taps shall not exceed 10 per cent above rated voltage unless otherwise specified.

11.033 Bushings

a. Bushings for use with transformers and other induction apparatus as covered by these standards shall be capable of withstanding the standard impulse and low-frequency tests required for the specified insulation class as given in Table 11.033.

b. Transformers and other induction apparatus should be equipped with bushings of an insulation class not less than that of the winding terminal to which they are connected unless otherwise specified.

Table 11.033

Standard Withstand Test Voltages for Apparatus Bushings

Insulation Class	Low Frequency Test					Impulse Test—Full Wave		
	Outdoor Bushings				Indoor Bushings (*c*) 1 Min Dry	Outdoor Bushings		Indoor Bushings (*c*)
	Large Apparatus (*a*)		Small Apparatus (*a*)			Large Apparatus (*a*)	Small Apparatus (*a*)	
	1 Min Dry	10 Sec Wet (*b*)	1 Min Dry	10 Sec Wet (*b*)				
col 1	col 2	col 3	col 4	col 5	col 6	col 7	col 8	col 9
Kv	Kv Rms	Kv Rms	Kv Rms	Kv Rms	Kv Rms	Kv Crest	Kv Crest	Kv Crest
1.2	..	..	10	6	..	..	30	..
2.5	21	20	15	13	20	60	45	45
5.0	27	24	21	20	24	75	60	60
8.66	35	30	27	24	30	95	75	75
15	50	45	35	30	50 (*d*)	110	95	110 (*d*)
25	70	60	70	60	60	150	150	150
34.5	95	80	95	80	80	200	200	200
46	120	100	120	100	..	250	250	..
69	175	145	175	145	..	350	350	..
92	225	190	225	190	..	450	450	..
115	280	230	280	230	..	550	550	..
138	335	275	335	275	..	650	650	..
161	385	315	385	315	..	750	750	..
196	465	385	465	385	..	900	900	..
230	545	445	545	445	..	1050	1050	..
287	680	555	680	555	..	1300	1300	..
345	810	665	810	665	..	1550	1550	..

Notes: (*a*) Large apparatus indicates transformers and other apparatus of corresponding importance rated above 500 kva, and small apparatus indicates transformers and other apparatus of corresponding importance rated 500 kva and below.

(*b*) Wet withstand values are based on water resistivity of 7000 ohms per inch cube, and precipitation rate of 0.2 inch per minute.

(*c*) Indoor bushings are those intended for use in indoor apparatus, except dry-type transformers, dry-type instrument transformers, and dry-type regulators. Indoor bushing test values do not apply to bushings used primarily for mechanical protection of insulated cable leads. A wet test value is not assigned to indoor bushings.

(*d*) Small indoor apparatus may be supplied with bushings for a dry test of 38 kv and impulse test of 95 kv.

11.034 Dielectric Tests—General

a. Standard low-frequency tests consist of an applied-potential test, an induced-potential test, or both.

b. The standard impulse test wave is a 1.5 × 40 microsecond wave, as defined in 22.115 of the Test Code.

c. Impulse tests shall be made only when specified and then only on the windings specified.

d. The sequence for standard dielectric tests shall be impulse test (when required) followed by the low-frequency tests.

e. The standard impulse test on a line terminal consists of one application of a reduced voltage full wave, two applications of a chopped wave, followed by one application of a full wave. Either, but not both, positive or negative waves may be used. Waves of negative polarity for oil-immersed apparatus and of positive polarity for dry-type or compound-filled apparatus are recommended and shall be used unless otherwise specified. If, in testing oil-immersed apparatus, the atmospheric conditions at the time of test are such that the bushings will not withstand the specified polarity wave, then a wave of the opposite polarity may be used.

f. The standard impulse test on the neutral of a Y-connected transformer, when brought out through a bushing, consists of two full waves having a crest voltage for the insulation class of the neutral. When applied directly to the neutral, these shall be 1.5 × 40 waves. When induced in the neutral by the application of 1.5 × 40 waves to other terminals, the wave shape shall be that resulting from the characteristics of the winding.

g. For impulse tests on transformers of very low inductance, see 22.117.

h. When apparatus covered by this standard is to be assembled in a common tank and interconnected and each transformer has been tested individually in advance according to its rating, the complete assembly shall be tested as a unit with 15 per cent lower test voltage than the lowest required by any of the components. As an alternative, the tests of the individual components may be omitted, in which case the complete assembly shall be tested as a unit at 100 per cent of the lowest test voltage required by any of the components.

11.035 Standard Impulse Tests

a. Chopped-wave Test

(1) For this test, the applied-voltage wave shall have a crest voltage and time to flashover in accordance with the table which appears in each section of these standards.

(2) The chopped wave shall be obtained by flashover of the bushing or of an external rod gap.

b. Full-wave Test. For this test, the applied-voltage wave shall have a crest value in accordance with the table which appears in each section of these standards.

c. Excitation during Impulse Tests. During the impulse tests (unless otherwise excepted in these rules) the transformer shall be excited at normal voltage and the impulse shall be timed within 30 electrical degrees of the crest of the normal voltage of opposite polarity. The normal-frequency excitation may be omitted by mutual agreement between manufacturer and purchaser.

11.036 Standard Applied-Potential Test

a. For transformers designed for delta connection or designed so that either terminal of a winding can be used as the line terminal, the applied-potential test shall be made by applying between each winding successively and all other windings and ground a low-frequency voltage from external source in accordance with the table which appears in each section of these standards.

b. For transformers with reduced insulation at the neutral, the applied-potential test shall be made by applying between the winding and all other windings and ground a low-frequency voltage from an external source in accordance with the table which appears in each section of these standards, depending upon the insulation class of the neutral end.

c. All other electric circuits and metal parts shall be grounded during the test.

d. The duration of the applied-potential test shall be 1 minute.

11.037 Standard Induced-Potential Test

a. (1) The induced-potential test for transformers that receive the full standard applied-potential test shall be made by applying between the terminals of one winding a voltage of twice the normal voltage developed in that winding unless this will produce a voltage between terminals of any other winding in excess of the low-frequency test voltage specified from Table 11.030. In this case the induced voltage developed between terminals of any winding shall be limited to the specified low-frequency test voltage for that winding.

(2) If testing circuit conditions are such that the induced-potential test just described does not produce the voltage required in (1) above between adjacent three-phase line terminals, additional tests shall be made to produce this voltage.

(3) For transformers with reduced insulation at the neutral, when neither the applied-potential tests nor the induced tests in (1) and (2) above produce the specified low-frequency test voltage corresponding to the insulation class of the line end between line terminals and ground (not necessarily between line terminals and neutral), then additional tests shall be made to produce this voltage.

b. The duration of the induced-potential test shall be established by the same number of cycles as for a 120-cycle 1-minute test except that it shall not exceed 60 seconds. These equivalents, for purposes of standardization, are as follows:

Frequency	*Duration, Seconds*
120 or less	60
180	40
240	30
360	20
400	18

Test Procedure

11.045 Where Tests Are to Be Made. Unless otherwise specified, tests shall be made at the factory only.

11.046 Methods of Making Tests. Tests shall be made in accordance with the American Standard Test Code, C57.22-1948.

EQUIPMENT FOR IMPULSE TESTING

Special equipment, of course, is necessary for impulse testing, and such tests are rarely made except at the factory where the transformer is built. The special equipment consists of an impulse generator, a potential divider, and measuring apparatus.

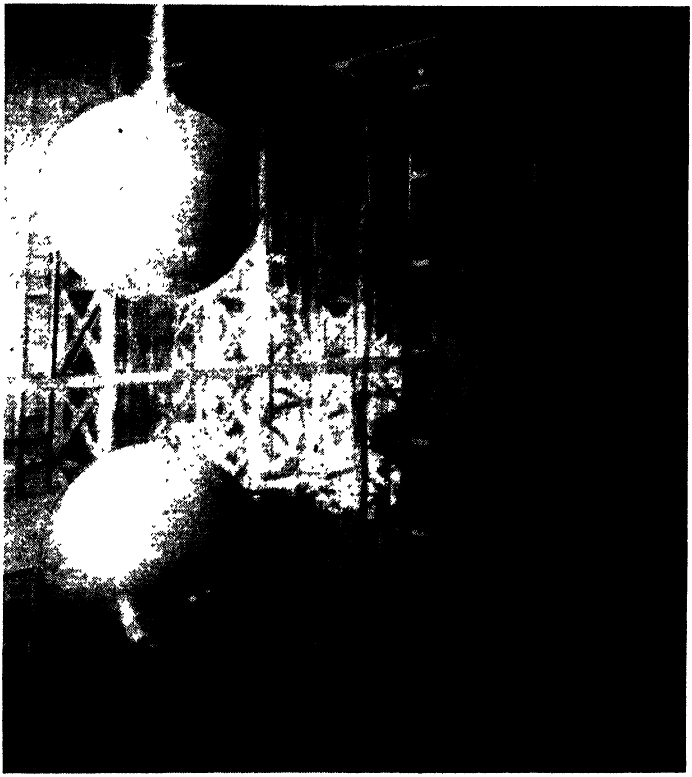


FIG. 94. Large impulse generator with sphere gap.

Impulse Generator. The impulse generator, or *lightning generator*, consists of a number of condensers so arranged that they can be charged in parallel and discharged in series. This enables the impulse voltage to be built up to any desired magnitude by increasing the number of condensers, but the problem of insulation becomes more difficult as the voltage increases. In one construction the condensers are arranged on a stairlike structure, with the grounded end of the circuit at the bottom and the other end high enough to insulate effectively for the highest voltage to be used. The parts of the structure and the supporting pillars are of insulating material. Impulse generators are in use which are capable of delivering 3,000,000 volts or more. Figure 94 shows such a generator.

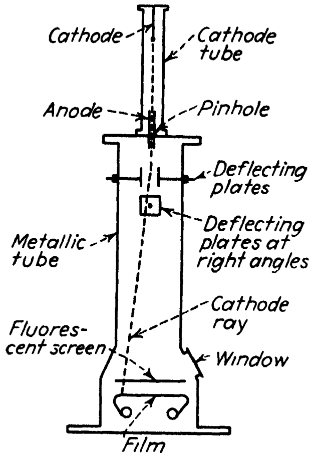


Fig. 95. Sketch of cathode-ray oscillograph.

Potential Divider. Two forms of potential divider are used. In one form a high-resistance wire is wound noninductively on a form and connected between the high-voltage lead and ground. Near the grounded end a tap is taken off so that a definite fraction of the applied voltage will appear between the tap and ground. This fractional voltage is then measured.

In the other form of potential divider two capacities in series are used: a small capacity near the high-voltage lead and a comparatively large capacity near the measuring instrument. Since the drop over each of two capacities in series is inversely proportional to the capacity, this arrangement gives a large voltage drop at the high-voltage end and a small proportional voltage for measurement.

Fig. 96. Cathode-ray oscillograph record.

Measuring Apparatus. The only measuring apparatus adequate for impulse testing is the cathode-ray oscillograph. In principle this consists of a vacuum chamber at the top of which is a cathode-ray tube. The cathode ray can be deflected by an electric or a magnetic field, and since it has no inertia, it can respond instantly to changes in such a field. Any kind of mechanical indicator is useless for this work because its response would be too slow on account of its inertia. The cathode ray affects a photographic film like light, so a film is used to record the movement of the ray.

The film is placed at the bottom of the vacuum chamber, and along the walls of the chamber are two sets of deflecting plates at right angles to each other. The voltage to be measured is connected to one set of plates, and the timing voltage to the other. When the impulse occurs, the ray is deflected and writes on the film a record of the size and shape of the impulse. The device is calibrated so that vertical distances on the film can be read in volts and horizontal distances as microseconds. Figure 95 is a schematic sketch of the cathode-ray oscillograph, and Fig. 96 is a sample of the record which it makes.

CHAPTER XI

TRANSFORMER POLARITY

The term *polarity*, as applied to a battery or to a direct-current generator, means that one terminal has a definite positive potential and the other a definite negative potential. This definition, however, does not apply to a transformer, for the transformer is used on an alternating-current circuit, and each terminal is alternately positive and negative with each alternation of the applied voltage. As applied to transformers, the term *polarity* refers to the relative instantaneous polarity in the two windings.

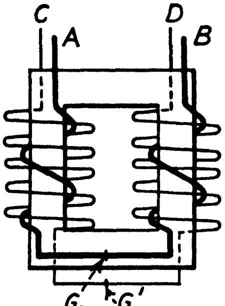


Fig. 97. Windings in same direction.

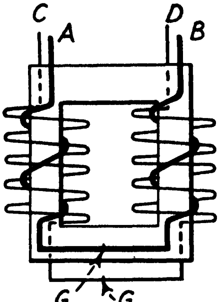


Fig. 98. Windings in opposite directions.

POLARITY OF SINGLE-PHASE TRANSFORMERS

Consider a core-form transformer as shown in Fig. 97. The heavy line *AB* represents the low-voltage winding, and the light line *CD* the high-voltage winding. If a voltage is applied to either winding, a magnetic flux will be set up in the core which will link both windings and will therefore induce voltage in both, and since the winding from *A* to *B* goes around the core in the same direction as the winding from *C* to *D*, the voltage in both windings will be in the same direction. That is, *A* will be positive with respect to B at the same instant when C is positive with respect to D.

If the direction of one of the windings around the core is reversed, as shown in Fig. 98, the flux in the core will induce voltages in opposite directions in the two windings. That is, A will be positive with respect to B at the instant when C is negative with respect to D.

In such transformers the leads from the high-voltage winding and from the low-voltage winding are usually on opposite sides of the core, as indicated on the figures, and the leads are generally brought out through the case in the order in which they come out of the coils. A transformer wound like Fig. 97, then, might have its leads brought out of the case as indicated in Fig. 99. If such a transformer is connected to an alternating-current line and adjacent leads from the high-voltage and the low-voltage windings are connected together (A to C or B to D, Fig. 99), the voltage between the remaining high-voltage and low-voltage leads will be less than the voltage across the high-voltage winding. The transformer is then said to have *subtractive* polarity. Similarly, if A and C are connected together in Fig. 98, the voltage from B to D will be greater than the voltage from C to D and the polarity will be *additive*.

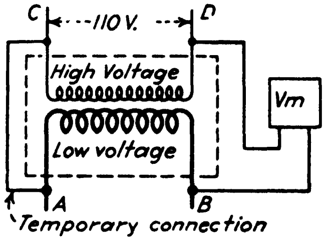


FIG. 99. Checking polarity with voltmeter.

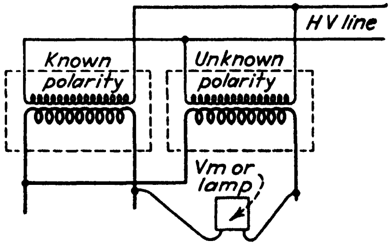


FIG. 100. Checking polarity with standard transformer.

Measurement of Polarity. The paragraph above suggests a method of determining the polarity of a transformer if it is not marked. In Fig. 99 connect lead A to lead C as shown, and apply a low voltage, *e. g.*, 110 volts, to the high-voltage winding. If the reading of a voltmeter connected from B to D is less than the reading from C to D, the polarity of the transformer is subtractive.

Caution. In making this test the voltage should be applied to the high-voltage winding and it should not exceed about 110 volts, both to avoid burning out a standard voltmeter and to avoid the danger of shock to the tester.

Another method of determining the polarity of a transformer is to check it, as shown in Fig. 100, against a transformer of the same ratio and of known polarity. The two transformers are connected in parallel on the high-voltage side as shown, and one pair of corresponding low-voltage leads is connected together. Now take a voltmeter or a lamp capable of standing double the normal voltage of one transformer, and connect it across the other two low-voltage leads. If double voltage is indicated, the two transformers are of opposite polarity, and if zero voltage is shown, the two are of the same polarity.

External Polarity. As far as the user is concerned, polarity refers to the arrangement of the external leads. It can be reversed by interchanging either the high-voltage leads or the low-voltage leads, *i.e.*, by crossing one pair of leads inside the case.

Polarity Marking. The question of polarity is unimportant when a single transformer is to be operated alone, but it is extremely important when two or more transformers are to be operated in bank. To simplify this problem the AIEE, the NELA, and the Power Club agreed on a system for marking transformers to indicate their polarity, and the system has been included in present American Standards. As applied to single-phase transformers its consists in marking the high-voltage leads H_1, H_2, etc., in the order of their position in the winding and similarly marking the low-voltage leads X_1, X_2, etc. The letter H_1 is applied to the high-voltage lead which leaves the case farthest to the right, facing the high-voltage side of the case (lead C, Fig. 99). The letters are applied to the low-voltage winding so that, when H_1 and X_1 are connected together, regardless of the location of X_1, the low voltage will subtract from the high voltage. For example, if lead C in Fig. 97 is marked H_1, lead A must be marked X_1 because it starts around the core in the same direction and will therefore have the same relative polarity. Similarly, if in Fig. 98 lead C is marked H_1, lead B must be marked X_1. Figure 101 shows the lead marking for a transformer of subtractive polarity, and Fig. 102 the corresponding marking for additive polarity. The great advantage of this system is that a polarity test is not necessary when transformers are to be connected in parallel or in a three-phase bank. In modern transformers polarity is always indicated by a diagram either in the form of a plate attached to the transformer or a printed diagram sent with the transformer.

Standard Polarity. Some years ago there was a difference between manufacturers as to which polarity should be standard for transformers of various classes. In 1920 and 1921, however, the NEMA adopted a standard which since then has been generally adhered to. This standard is embodied in the American Standards as follows:

Polarity of Single-phase Transformers

a. Additive polarity shall be standard for all single-phase transformers in sizes 200 kva and below having high-voltage ratings 8,660 and below (winding voltage).

b. Subtractive polarity shall be standard for all other single-phase transformers.

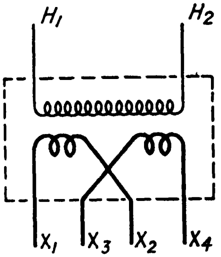


FIG. 101. Subtractive polarity.

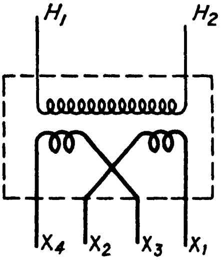


FIG. 102. Additive polarity.

Internal Polarity. In addition to the effect on the external polarity of the transformer, the relative direction of the two windings has a bearing on the voltage stress on the insulation between the windings, although this is of no practical importance in transformers whose low voltage is less than 4,600 volts. If a transformer is connected to a single-phase line which is free from grounds or which has its neutral solidly grounded, the middle point of the transformer winding will be at ground potential, just as though the windings in Figs. 97 and 98 were grounded at the points *G* and G_1. This is the ideal operating condition. If an end coil of the low-voltage winding is adjacent to the end coil of the high-voltage winding of the same polarity, the real voltage between them is evidently the difference between their potentials above ground; *i.e.*, the voltage stress on the insulation at this point is $\frac{1}{2}E_1 - \frac{1}{2}E_2$. This condition is shown in Fig. 97, where the A end of the low-voltage winding is mechanically adjacent to the C end of the high-voltage winding and of the same relative polarity. The voltage from C to A is evidently equal to the voltage from G_1 to C minus the voltage from G to A. But if an end coil of the low-voltage circuit is adjacent to the end coil of the high-voltage circuit having opposite polarity, the voltage stress on the insulation is $\frac{1}{2}E_1 + \frac{1}{2}E_2$. This is the condition in Fig. 98. In a transformer whose ratio is 23,000:6,900, for instance, the voltage stress on the insulation between windings during operation would be $\frac{23{,}000}{2} - \frac{6{,}900}{2} = 8{,}050$ volts with the arrangement shown in Fig. 97, while it would be $\frac{23{,}000}{2} + \frac{6{,}900}{2} = 14{,}950$ volts with the arrangement shown in Fig. 98. Under actual operating conditions it is seldom that both high-voltage and low-voltage lines are entirely free from grounds, and any condition may exist from the ideal state described to the worst possible voltage stress, which would occur when H_1 and X_2, or H_2 and X_1 were grounded at the same time. If this occurred, the worst stress that could come on the insulation between primary and secondary in a transformer wound like Fig. 97 would be the full voltage of the high-voltage winding. In a transformer wound like Fig. 98 the corresponding stress might be the sum of the high and the low voltages.

Usually the leads will be brought out of the case to give subtractive polarity when the transformers are arranged as in Fig. 97 and additive polarity when arranged as in Fig. 98, so in general it may be said that, if the lower voltage is 4,600 or more, a transformer with subtractive polarity is preferable.

POLARITY OF THREE-PHASE TRANSFORMERS

Three-phase transformers are electrically equivalent to three single-phase transformers built on a common core and mounted in a single case. The connections between phases are usually made inside the case, and three high-voltage leads and three low-voltage leads are brought out as in Fig. 103, where A-B-C indicate the high-voltage leads and X-Y-Z the low-voltage. In order to parallel such transformers it is necessary to know the relative phase sequence as well as the relative polarity of the leads. That is, if the primary voltages reach their maximum in the order A, B, C, do the secondary voltages reach their maximum in the order X, Y, Z or in the order X, Z, Y? The interphase connections inside the case can be made in several ways with different results on polarity. To promote uniform practice the AIEE and the NEMA have agreed on standards.

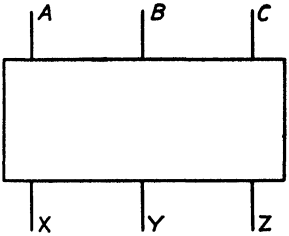
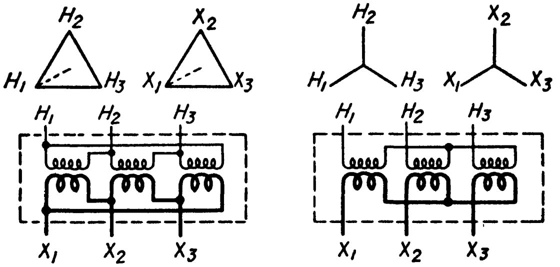
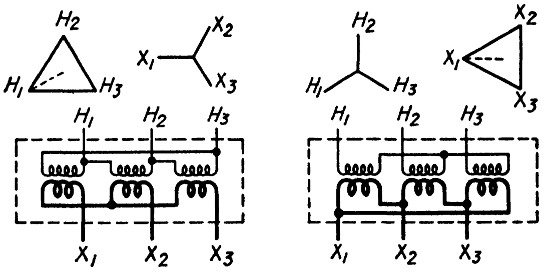


Fig. 103. Three-phase transformer.

Standard Lead Markings. The three high-voltage leads connected to the full windings are marked H_1, H_2, and H_3, respectively, and are brought out of the case in order, with H_1 to the right, facing the high-voltage side of the case. The letters X_1, X_2, and X_3 are



Group 1-Angular displacement 0°



Group 2-Angular displacement 30°

Fig. 104. Standard three-phase polarity.

then applied to the low-voltage leads so that X_1 designates the lead nearest in phase with H_1 and so that the phase sequence is in the same order as on the high-voltage side. The actual phase position of X_1 depends on the connections inside the case. Four different combinations of high-voltage and low-voltage connections are recognized: delta-delta, Y-Y, delta-Y, and Y-delta. These are shown in Fig. 104 with the corresponding lead markings according to the rule The term *angular displacement* refers to the angle between the vector drawn from H_1 to the three-phase neutral and that drawn from X_1 to the three-phase neutral.

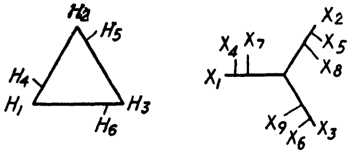


FIG. 105. Standard three-phase tap numbering.

Transformers so marked can be operated in parallel by connecting similarly marked leads together, provided that they have the same angular displacement and provided also that their ratios, voltages, resistances, and reactances are such as to permit parallel operation.

Three-phase Transformers with Taps. When taps are brought out of a three-phase transformer, the leads from the full windings are marked as above. The first set of taps is marked H or X as the case may be, with subscripts 4, 5, and 6, and the second set of taps uses the subscripts 7, 8, and 9. This is illustrated in Fig. 105.

CHAPTER XII

USUAL TRANSFORMER CONNECTIONS

Included in this chapter are diagrams of single-phase transformers showing the connections commonly used for single-phase distribution and for polyphase distribution and transmission. Any of the connections shown may be used to step the voltage either up or down. The diagrams show transformers having a single high-voltage winding and a series-parallel low-voltage winding. This corresponds to the common type of distribution transformer, for example, 2,400 to 240–120 volts. The same connections are, however, used for transformers of any voltage.

Low-voltage secondary circuits which supply interior wiring systems are required by the National Board of Fire Underwriters to be grounded if they can be so grounded that the maximum voltage to ground does not exceed 150 volts, and it is recommended that they be grounded if the voltage to ground exceeds 150 volts but does not exceed 300 volts. This applies to single-phase and to polyphase circuits. The ground connections on customers' premises are not considered here. The ground connection at the transformer should preferably be made at a neutral point if such a point is available. If not, it can be made at any convenient point. Suitable grounding points are indicated in the diagrams. The best grounds are connections to systems of water piping. If these cannot be had, pipe grounds made by driving a piece of galvanized pipe about 8 feet into the ground at the base of the poles are much used. The ground wire from the transformer is carried down the pole in a wooden molding and solidly connected to the top of the pipe.

Single-phase Connections. Figure 106 shows a single-phase transformer connected between a high-voltage line and a low-voltage line. The low-voltage windings are connected in parallel. Such a connection might be used if a single customer were to be served with 120 volts for lights. Figure 107 is similar to Fig. 106 except that the low-voltage windings are connected in series so that the delivered voltage is 240.

If the customer's load is large enough to be divided into two or more circuits, or if several customers are to be served from the same transformer, the use of the three-wire distribution results in better regulation or less copper in the lines than a two-wire system. Figure 108 shows the same transformer as before, connected for a single-phase three-wire system, giving 120 volts from each outside wire to neutral and 240 volts between outside wires. These three figures show single-phase transformers operating alone, and no attention need be paid to their polarity.

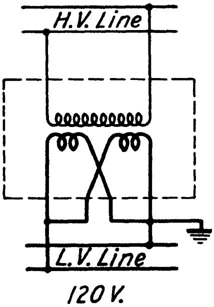


FIG. 106. Single-phase, parallel.

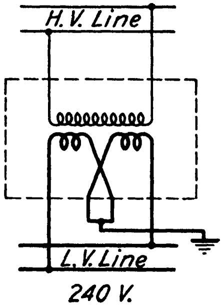


FIG. 107. Single-phase, series.

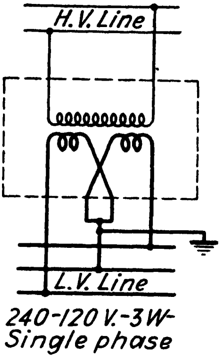


FIG. 108. Single-phase, three-wire.

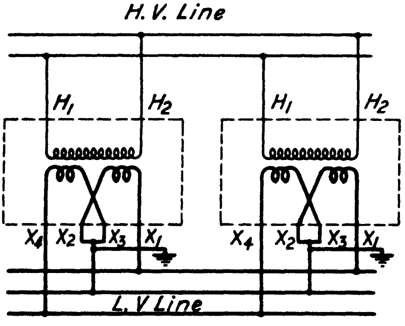


FIG. 109. Parallel connection of two single-phase transformers to a three-wire circuit.

Figure 109 shows two single-phase transformers operating in parallel to supply a single-phase three-wire system. In such a case terminals of the same relative polarity must be connected together, or a short circuit will be caused which will blow the primary fuse and may damage the transformers. As a general rule the parallel operation of small transformers should be avoided, because both the first cost and the losses of two small transformers will be greater than those of a single transformer large enough for the total output. This general rule is modified by the fact that sometimes small transformers which are on hand can be connected in parallel to save the purchase of a new transformer. Even in such a case, however, the relative losses should be checked to find if the lower losses in the new transformer will not make it more economical in the long run.

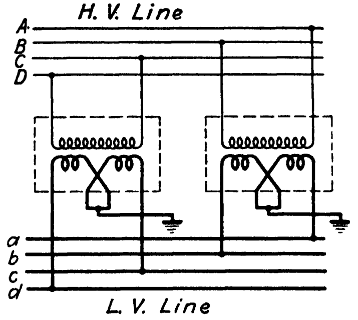


FIG. 110. Two-phase, four-wire.

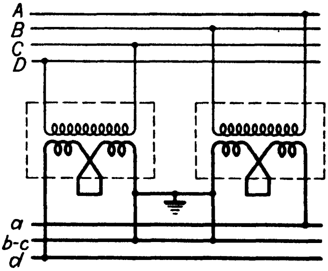


FIG. 111. Two-phase, three-wire.

In large transformers the difference between losses is not so great, and it is frequently desirable to operate such transformers in parallel. A discussion of the factors involved in parallel operation will be found in another chapter.

Two-phase Connections. Two-phase systems consist of two single-phase circuits whose voltages are 90 electrical degrees apart; *i.e.*, the voltage in one circuit passes through its maximum at the instant when the voltage in the other circuit is passing through zero. The two circuits are often entirely separate and insulated from each other. In this case they can be treated as single-phase circuits as shown in Fig. 110. Sometimes one common line is run for the two circuits, as shown on the low-voltage side in Fig. 111. This forms a two-phase, three-wire system, and the common line (*b-c* in the figure) must carry $\sqrt{2}$ times the current in line *a* or *d*.

Three-phase Connections. Three single-phase transformers can be connected together in a number of ways to transform three-phase power from one voltage to another. The connections shown here are those adopted by NEMA. They result in phase relations the same as those adopted as standard for three-phase transformers by the ASA. It is necessary in such connections to know the polarity of the transformers as well as the connections between leads.

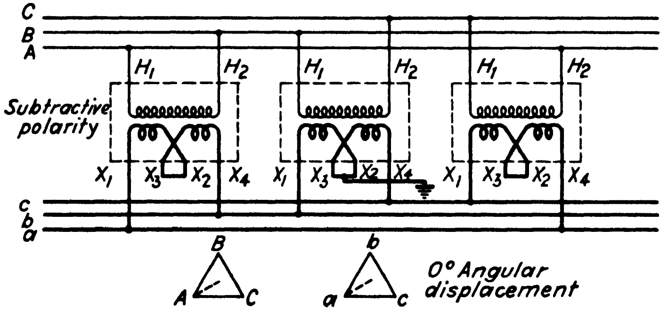


FIG. 112. Three single-phase transformers, subtractive polarity, connected delta-delta for three-phase transformation

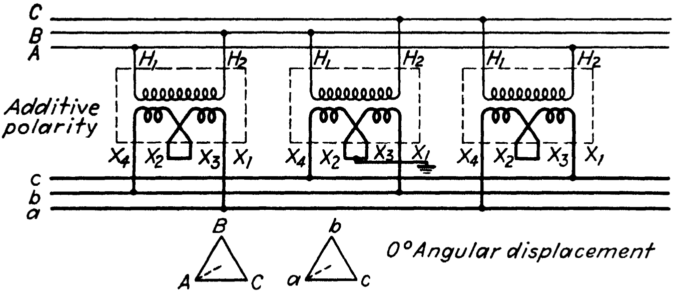


FIG. 113. Three single-phase transformers, additive polarity, connected delta-delta for three-phase transformation.

Figure 112 shows a delta-delta connection for transformers of subtractive polarity. The low-voltage vector triangle *abc* occupies the same relative position as the high-voltage triangle *ABC*. Figure 113 shows the same connection for transformers of additive polarity. It will be seen that the connections on the high-voltage side are exactly the same in the two figures and that the right-hand low-voltage lead of each transformer in Fig. 112 makes the same connection as the corresponding left-hand lead in Fig. 113. In other words, X_1 from each transformer is connected to the same line in Fig. 112 as in Fig. 113.

Figure 114 is electrically exactly the same as Fig. 113. It shows another way of making the same connection which may be more

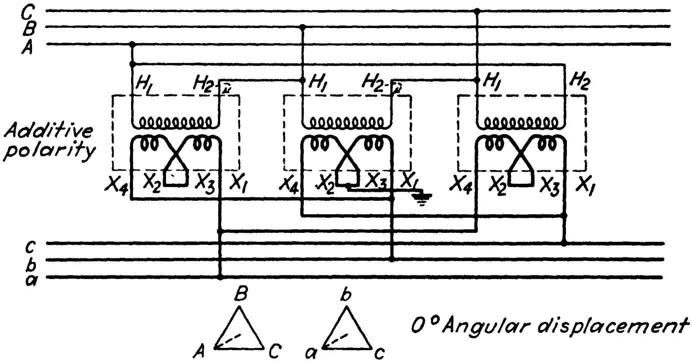


FIG. 114. Similar to Fig. 113 except that the delta connections are made at the transformer.

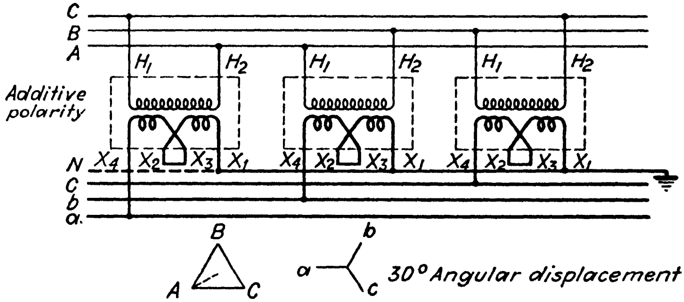


FIG. 115. Three single-phase transformers, additive polarity, connected delta-Y.

convenient in some circumstances. The voltage rating of transformers for delta-delta connection is the same as the voltage from line to line of the circuit to which they are to be connected.

Figure 115 shows a delta-Y connection. The voltage rating of the delta side is the same as the voltage of the line, but the voltage rating of the Y-connected side of the transformer is $1/\sqrt{3}$ times the line voltage. Frequent use is made of this connection by connecting the two halves of the low-voltage winding in parallel instead of in series, as shown in the figure, and running a fourth, or neutral, wire *N*, as indicated by the dotted lines. One hundred and twenty volts is then available in single-phase from *N* to each of the three lines *a*, *b*, and *c* for lighting, and at the same time 208 volts, three-phase, is available on *abc* for motors. Figure 115 shows transformers of additive polarity, and Fig. 116 is the same connection for transformers of subtractive polarity.

In large power transformers the delta-Y connection is much used for step-up transformers. The Y connection on the high-voltage side gives a neutral point for grounding the high-voltage circuit and also a lower voltage per transformer than would be required for delta connection. This means a smaller number of high-voltage turns and a larger wire, and it also simplifies the insulation somewhat.

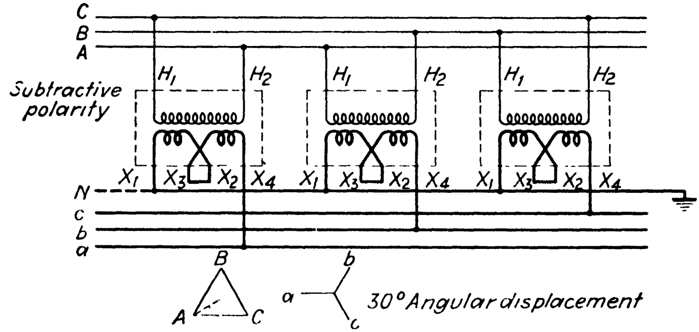


FIG. 116. Three single-phase transformers, subtractive polarity, connected delta-Y.

Figures 117 and 118 show the Y-delta connection for transformers of additive and subtractive polarity, respectively. A common example of this system is a three-phase 4,160-volt line in which the neutral, as indicated by the dotted line, is run back to the source of power. Standard 20:1 distribution transformers are connected from *N* to each of the lines, and their secondaries are connected in delta to give 120 or 240 volts, three-phase.

For large power transformers the Y-delta is used for step-down transformers, for the same reasons as explained above.

Figures 119 and 120 show the Y-Y connection for transformers

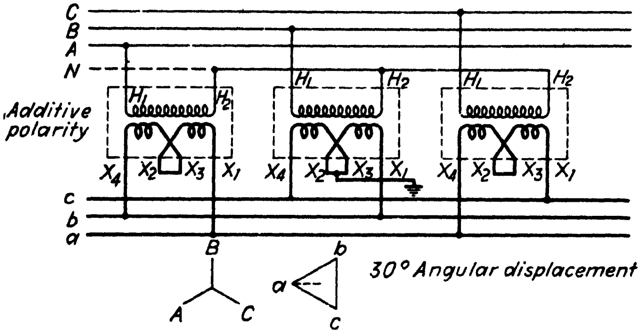


Fig. 117. Three single-phase transformers, additive polarity, connected Y-delta.

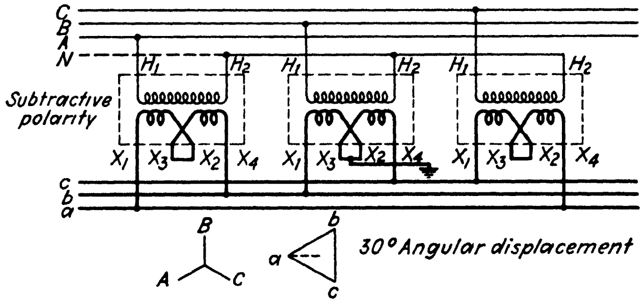


Fig. 118. Three single-phase transformers, subtractive polarity, connected Y-delta.

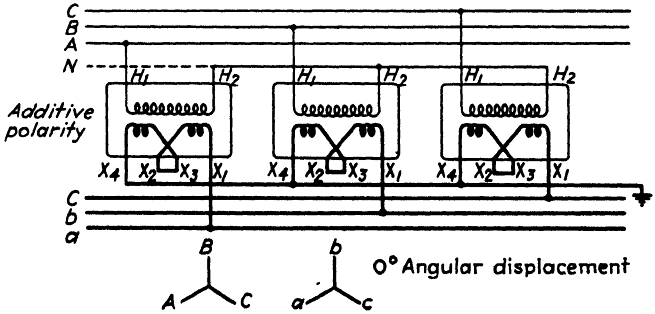


Fig. 119. Three single-phase transformers, additive polarity, connected Y-Y.

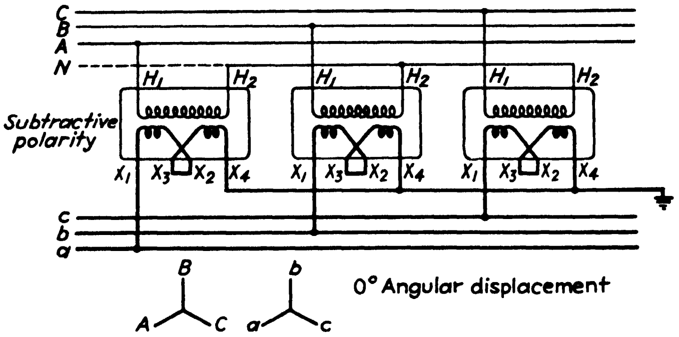


FIG. 120. Three single-phase transformers, subtractive polarity, connected Y-Y.

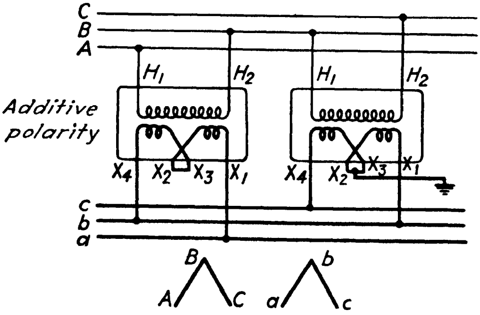


FIG. 121. Open-delta, or V-V, connection, additive polarity.

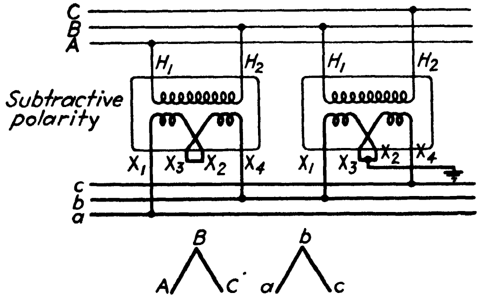


FIG. 122. Open-delta, or V-V, connection, subtractive polarity.

of additive and subtractive polarity, respectively. This connection should be used with caution because of the possibility of distorted voltages. To deliver a sine wave of voltage it is necessary to have a sine wave of flux in the core, but owing to the characteristics of the iron, a sine wave of flux requires a third-harmonic component in the exciting current. As the frequency of this component is three times the frequency of the circuit, it tends to flow toward the neutral point in all three transformers at the same time. If the neutral is isolated, the triple-frequency current cannot flow. The flux in the core, therefore, cannot be a sine wave, and the voltage will be distorted. If a fourth wire *N*, shown by the dotted line, is run back from the transformer neutral to the source of power, a path is provided for the triple-frequency current and the difficulty is overcome. Another way of avoiding this trouble is to supply each of the transformers with an auxiliary winding. The three auxiliary windings are connected in delta, and this provides a circuit in which the triple-frequency component of the exciting current can flow. A sine wave of voltage applied to the primary will then result in a sine wave of voltage on the secondary.

Figures 121 and 122 show the open-delta, or V-V, connection which is much used where small amounts of three-phase power are required. On account of the class of service in which this connection is used, there is rarely any question of parallel operation, and the connection is usually made as in Fig. 122, regardless of polarity, as long as the transformers are alike. This is a matter of convenience. The advantage of this connection is that it takes only two transformers instead of three. It is therefore simpler to install and makes a neater appearance on the pole. Its disadvantage is that it requires, in transformer capacity, 115 per cent of the kilovolt-ampere output, and its regulation is a little worse than that of a system using three transformers.

CHAPTER XIII

PARALLEL OPERATION OF TRANSFORMERS

Perfect parallel operation of two or more pieces of electrical apparatus means that the common load divides among the separate units in proportion to their rated capacity and that the numerical sum of the currents in the separate units equals the line current.

Conditions for Parallel Operation. In the case of transformers two conditions must be fulfilled for perfect parallel operation: The ratio of high-voltage turns to low-voltage turns must be the same in all units, and the voltage drop from no load to full load must be the same in all units, both in magnitude and in phase position. The first of these conditions is obvious, for a difference in ratio causes a difference in voltage at all loads, and the transformer having the higher voltage will, of course, carry the larger load.

The necessity of the second condition will also be evident. Suppose that two transformers have the same open-circuit secondary voltage, say 100, but that one transformer has a full-load voltage of 96 and the other transformer a voltage of 98; *i.e.*, at full load one transformer has a voltage drop of 4 volts and the other a drop of 2 volts. If the two are connected to a common load equal to the sum of their capacities, the voltage at the terminals of both must be the same and will lie somewhere between 96 and 98 volts. The drop in the first transformer will therefore be less than 4 volts and its current must consequently be less than its rated full-load current. Similarly, in the second transformer the voltage drop will be more than 2 volts and the current more than its rated current.

Voltage Drop in a Transformer. The total voltage drop in a transformer, or the impedance drop, is the resultant of two components: the resistance drop, which depends only on the ohmic resistance of the windings and is in phase with the current and the reactance drop, which depends on the magnetic leakage between the high-voltage winding and the low-voltage winding and is 90 degrees out of phase with the current. This relation is shown in Fig. 123.

Current Division in Parallel Circuits. When two transformers having the same ratio and the same percentage of impedance are connected in parallel, each will carry current in proportion to its rated capacity, but unless the relative amount of resistance and reactance is the same in both, the sum of the currents will be greater than the current in the line. This is caused by the phase difference between the currents in the two transformers and can be explained as follows:

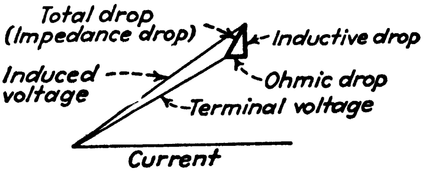


FIG. 123. Voltage drop in a transformer.

Suppose that any two parallel circuits A and B (Fig. 124) are connected between an alternator and its load. The current will divide at c and flow through A and B in parallel. The current ineach circuit will be numerically equal to the voltage drop from c to d divided by the impedance of the circuit and will lag behind the voltage cd by an angle determined by the ratio of reactance to resistance. This angle is not necessarily the same for both circuits, and the two currents, therefore, are not necessarily in phase with each other.

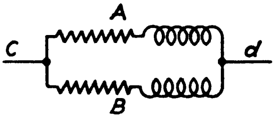


FIG. 124. Parallel circuits with resistance and reactance.

A vector diagram showing this condition is shown in Fig. 125, where OE represents the voltage drop cd in Fig. 124, OA is the current in circuit A (equal to the voltage drop cd divided by the impedance of circuit A) and lags behind OE by the angle θ_A (whose tangent is the ratio of reactance to resistance in circuit A). Similarly OB is the current in circuit B and lags behind OE by the angle θ_B. Evidently then if the ratio of reactance to resistance in circuit A differs from that in circuit B, θ_A will not equal θ_B, and hence OA and OB will not coincide in direction with OI, and their numerical sum will be greater than OI.

Load Division between Transformers. If transformers will not divide the load correctly when connected in parallel, it is important to know which will carry the excess load and how great the excess will be. This can be found by means of a diagram similar to Fig. 125. It is necessary to know the resistance and reactance of each transformer. These can usually be obtained from the manufacturer, or the resistance and the impedance can be measured on the transformer itself. From these measurements the reactance is calculated by the formula

$$\text{Ohms reactance} = \sqrt{(\text{ohms impedance})^2 - (\text{ohms resistance})^2}$$

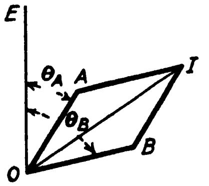


FIG. 125. Division of current in two parallel circuits.

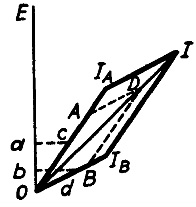


FIG. 126. Construction to find load division between two transformers.

The load diagram can now be constructed. Assume a line OE (Fig. 126), to represent the impedance voltage drop within the transformer. This line is used merely as a reference line, and its length is not important. Lay off from O on OE a distance Oa equal to the resistance of transformer A, and from a to the right lay off ac equal to the reactance of transformer A. Through O and c draw a straight line, which will represent the phase of the current in transformer A with reference to the impedance voltage OE. Similarly, lay off Ob and bd equal, respectively, to the resistance and reactance of transformer B, and draw a line through O and d to give the phase of the current in transformer B. Now the current in each of two parallel circuits is inversely proportional to the impedance; therefore on Oc lay off a distance OA equal to the impedance of transformer B, and on Od lay off OB equal to the impedance of transformer A, and complete the parallelogram $OBDA$. The diagonal of this parallelogram gives the phase of the load current with respect to OE. On OD lay off OI equal to the total load current, and resolve along Oc and Od to get OI_A and OI_B, respectively. The lengths of these lines then represent the actual currents in transformers A and B, to the same scale as was used in laying off OI.

It will be noted that the proportion between OI_A, OI_B, and OI is not changed by a change in the length of OI; also that no account is taken of the voltage on the load. It follows that the distribution of load between transformers connected in parallel is independent of the amount and power factor of the load if the ratio of transformation is the same in both transformers.

In practical transformers having the same ratio and impedance but different resistance and reactance it will be found that the sum of the currents in two paralleled transformers will rarely if ever exceed the line current by as much as 10 per cent, and usually the excess will be much less than this. Hence the difference in impedance will usually control the division of current between transformers, and the ratio of resistance to reactance need not be considered.

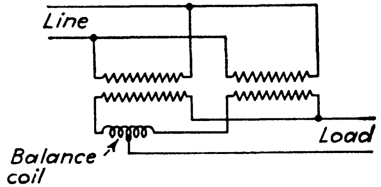


FIG. 127. Parallel operation with balance coil.

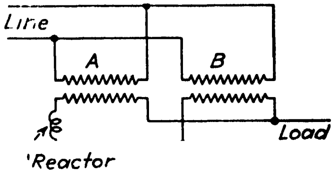


FIG. 128. Parallel operation with reactor.

Parallel Operation of Dissimilar Transformers. Even though transformers differ in ratio or in impedance or both, they can still be operated in parallel by the use of a suitable balance coil or reactor. Balance coils can be used to compensate for differences in both turn ratio and impedance. They are small autotransformers designed for a voltage equal to the difference between the full-load voltages of the transformers which are to be connected in parallel and having the number of turns in the two parts of their winding inversely proportional to the rated currents of the transformers. Figure 127 shows a balance coil connected between two transformers. If the tap in the balance coil is in the middle of the winding, the current in both halves of the balance coil and consequently in the two transformers will be the same. Such a balance coil is suitable for two transformers of the same rating. If one of the transformers has a larger rating than the other, the tap in the balance coil must be nearer the large transformer so that the ampere turns in the two parts of the balance coil will be equal when rated current is flowing in the two transformers.

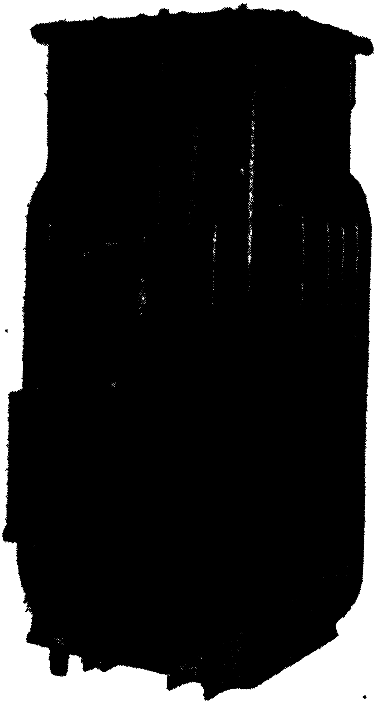


FIG. 129. No-winding reactor mounted on a transformer lead.

Usually transformers which are to be connected in parallel are alike in ratio, but they may differ in impedance. In such a case a small reactor may be connected in series with the transformer of low impedance so as to equalize the two and thus permit satisfactory parallel operation. For instance, if transformer *A* (Fig. 128) has an impedance of 3 per cent and *B* has 4 per cent, an external reactor may be connected in series with A to add 1 per cent impedance.

As far as the principle is concerned, a balance coil or a reactor may be designed for use in either the high-voltage or the low-voltage side of a transformer. It is usually more convenient to put it in the low-voltage side, however, because of the smaller amount of insulation required. Sometimes the required additional reactance can be obtained by running one of the low-voltage leads through an iron core containing an air gap but without a winding. The flux induced in the core by the transformer current links with the lead to give the reactive voltage needed. Figure 129 shows such an arrangement.

CHAPTER XIV

PHASE TRANSFORMATION

By phase transformation is meant a change in the number of phases in a polyphase system, either with or without a simultaneous change in voltage. Most of the electric power in this country is generated and distributed as three-phase current. There are still a number of circuits which serve two-phase motors, however, and which require two-phase power. Other circuits supply single-phase power for lighting, arc welding, and electric heating. And still other circuits supply six-phase power to operate rotary converters. Large rectifiers sometimes take twelve or more phases.

Any of these circuits, fortunately, can be fed from the usual three-phase power system by means of suitable transformers. If no voltage transformation is involved, or if the voltage ratio is low, it is economical to use autotransformers, which are discussed in another chapter.

In the present chapter, several of the commonly used connections for phase transformation are given. For simplicity it is assumed that the output in each line is 10 amperes and that the voltage between lines is 100 volts. The transformer ratio is also assumed to be 1:1. It is therefore possible to apply the figures below for volts and amperes to transformers of any size and voltage by multiplying by the ratio of volts, amperes, or kilowatts, as the case may be.

THREE-PHASE TO SINGLE-PHASE

Probably the commonest phase transformation is the connection of a single-phase load to a three-phase line, and many attempts have been made to do this so as to get a balanced three-phase load. Only two methods are known, however, for the accomplishment of this result: (1) to divide the load into three equal parts and connect one part to each phase or (2) to use a three-phase rotating machine between the three-phase line and the single-phase load. The first method is desirable and often practicable. The second method is usually out of the question on account of the expense. If the single-phase load cannot be divided, the best plan is to connect it to one phase of the three-phase system and trust to other single-phase loads connected to other phases to balance the system. As a matter of fact, an unbalanced load is not very objectionable unless the unbalance is large. A majority of large three-phase generating plants carry single-phase loads distributed among the three phases, as well as polyphase loads. Such systems are rarely if ever exactly balanced, but never far unbalanced.

Open Delta for Single-phase Loads. It may be of interest to show the fallacy of several of the three-phase to single-phase connections which have been proposed. One such scheme is the open-delta connection of two transformers with their secondaries in series, as shown in Fig. 130. The single-phase load is connected from *a* to *c*, as shown, which gives the same voltage as *ab* or *bc*. The load current flows through both transformers, and since it is a single-phase current, no current can flow to or from the line *B* and lines *A* and *C* must carry the whole primary current. Exactly the same condition would exist if the load were connected to a single transformer connected from *A* to *C*, except that the investment would be half as great and the losses half as great.

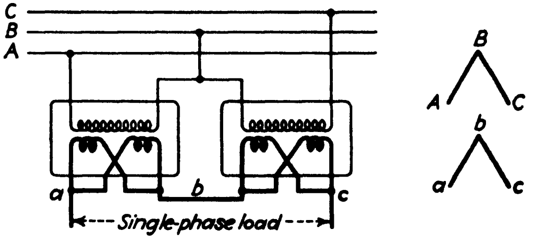


FIG. 130. Proposed transformation, three-phase to single-phase.

Delta Connection with One Secondary Reversed. Another scheme which has been proposed is the use of three transformers connected as in Fig. 131. This is similar to the usual delta-delta connection except that one corner of the secondary delta is open and the secondary of one transformer is reversed. The connection is similar to that described above except that another transformer has been added. As before, the line *B* can carry no current. Two transformers connected in parallel on the primary side between lines *A* and *C* and in series on the secondary side would give exactly the same conditions as are given by the three transformers in this scheme, except that the cost and the losses would be two-thirds as great.

Scott Connection with Secondaries in Series. A third proposal is to use the Scott connection to transform three-phase to two-phase and then put the two phases in series, as shown in Fig. 132. This will, of course, give a single-phase voltage, but it is interesting to see what happens when a current flows. Suppose that the transformers have a 1:1 ratio and that each of the two-phase voltages is 100 volts. Then the single-phase resultant voltage will be 100 × 1.414 = 141.4 volts. Now suppose that a 10-ampere load is put on the single-phase circuit. Since the primary of the teaser transformer *B* is connected to the 87 per cent tap, it must carry a current of 10 ÷ 0.87 = 11.5 amperes, and this must obviously be

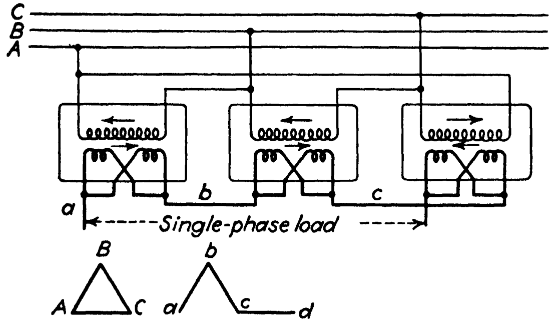


FIG. 131. Proposed transformation, three-phase to single-phase.

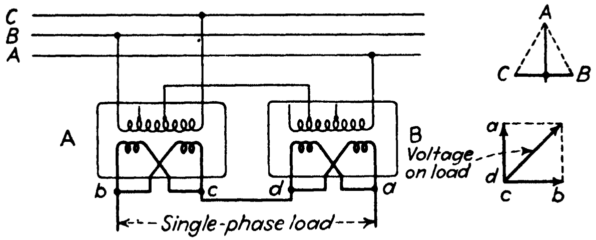


FIG. 132. Proposed transformation, three-phase to single-phase.

the difference between the currents in the two halves of the main transformer *A*. But the total ampere turns in the primary winding of *A* must be equal to the total ampere turns in its secondary winding, or 10 amperes × 100 per cent turns. Therefore, we have the two equations $50\% X + 50\% Y = 100\% \times 10$, and $X - Y = 11.5$, where *X* is the current in one half of the primary winding of *A* and *Y* is the current in the other half.

Solving these two equations we find that $X = 15.75$ amperes and $Y = 4.25$ amperes. The line *B*, therefore, will carry 15.75 amperes, of which 11.5 amperes will return to the generator by way of the line *A* and 4.25 amperes by way of the line *C*. The rating of each transformer will be

$$\frac{10 \text{ amperes} \times 100 \text{ volts}}{1{,}000} = 1 \text{ kva}$$

or a total of 2 kva for the bank, while the total single-phase output is

$$\frac{10 \text{ amperes} \times 141.4 \text{ volts}}{1{,}000} = 1.414 \text{ kva}$$

Thus the transformers are 40 per cent larger than the single-phase output, and the load current is not equally distributed among the three line wires.

It can be seen, therefore, that a single-phase load will not give a balanced condition in a three-phase line. This is further confirmed by the fact that three-phase power is continuous whereas single-phase power is pulsating. To connect the two, therefore, it would be necessary to have a rotating machine so that the pulsations could be stored in the inertia of the rotor.

THREE-PHASE TO TWO-PHASE

It is frequently desirable to transform from three-phase to two-phase, or vice versa. A number of different transformer connections are possible for this service, but only three are of any commercial importance, and of these the Scott connection is used almost to the exclusion of the others.

Scott Connection. Figure 133 shows the Scott connection. It consists of two transformers having 50 and 86.6 per cent taps on the three-phase side. One transformer, called the *main transformer*, is connected between two of the three-phase lines, as shown, and the *teaser transformer* is connected between the third line and the 50 per cent tap of the main transformer, using the 86.6 per cent tap of the teaser. The secondary output is

$$2 \times 10 \text{ amperes} \times 100 \text{ volts} = 2 \text{ kva}$$

for the bank, and the currents and voltages in different parts of the windings are as shown. It will be noted that the ampere turns in the primary winding of the main transformer apparently do not equal the ampere turns in the secondary winding. The reason is that the currents in the two halves of the primary winding differ in phase from the current in the secondary winding and also from each other. The components which are in phase with the secondary current will just balance the secondary ampere turns, while the component at right angles to the secondary current in one half of the primary winding balances the similar component in the other half.

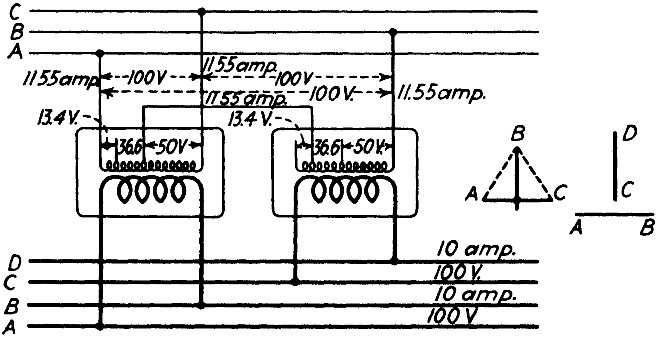


FIG. 133. Scott connection, three-phase to two-phase.

Example: What are the currents and voltages in a Scott-connected bank of transformers operating from 6,900 to 2,500 volts with a load of 1,000 kva?

Solution: Secondary voltage is 2,500 volts.

In Fig. 133 the secondary current is 10 amperes and the output is 2 kva. Therefore in this case the secondary current is

$$10 \text{ amperes} \times \frac{1{,}000 \text{ kva}}{2 \text{ kva}} \times \frac{100 \text{ volts}}{2{,}500 \text{ volts}} = 200 \text{ amperes per phase}$$

Primary voltage across the main transformer is 6,900 volts.

Primary voltage across the teaser transformer is

$$86.6 \text{ volts} \times \frac{6{,}900 \text{ volts}}{100 \text{ volts}} = 5{,}975 \text{ volts}$$

and the primary current is

$$11.55 \text{ amperes} \times \frac{1{,}000 \text{ kva}}{2 \text{ kva}} \times \frac{100 \text{ volts}}{6{,}900 \text{ volts}} = 83.7 \text{ amperes per phase}$$

As a check,

$$\frac{83.7 \text{ amperes} \times 6{,}900 \text{ volts} \times \sqrt{3}}{1{,}000} = 1{,}000 \text{ kva}$$

The transformers needed for Scott connection correspond in size to transformers having an output of

$$\frac{10 \text{ amperes} \times 100 \text{ volts} + 11.55 \text{ amperes} \times 100 \text{ volts}}{2}$$

$$= 1{,}078 \text{ volt-amperes}$$

and since two are required, the transformers are equivalent to 107.8 per cent of the output rating if the two are of the same size. It is possible to save a little of the material if the two transformers are not duplicates, but usually they are made alike, as indicated in Fig. 133.

Although the sketch and description of the Scott connection have assumed that the transformation is from three-phase to two-phase, it can be used equally well in transforming from two-phase to three-phase, and the same is true of the following connections.

Taylor Connection. Another three-phase to two-phase connection which is sometimes used is the Taylor connection, shown in Fig. 134. It requires three single-phase transformers with special taps, connected in delta, or a corresponding three-phase transformer with taps. The taps are located in the delta-connected windings of the two-phase side so that the voltage *AB* in the figure is perpendicular to the voltage *CD* and equal to it, thus giving the required two-phase relation. Evidently, then, *AB* also is equal to *BC* and to *CA* in length, and it is therefore possible to take three-phase power from the lines *ABC* at the same time as two-phase power is being taken from *AB* and *CD* at the same voltage.

As the amount of three-phase power which is drawn from the bank is increased, the available two-phase power is decreased. The relation is shown in Fig. 135. For example, if the bank is loaded to 50 per cent of its rating with two-phase power, the available three-phase power is 46 per cent of the bank rating, as indicated by the dotted lines in Fig. 135.

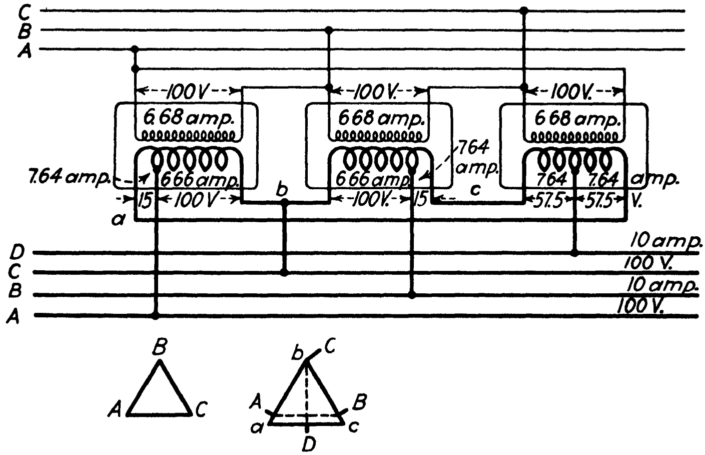


FIG. 134. Taylor connection, three-phase to two-phase.

The equivalent size of transformer for the transformer having a middle tap is 773 volt-amperes and for each of the others 724 volt-amperes. The total of the transformers, therefore, is 111 per cent of the output.

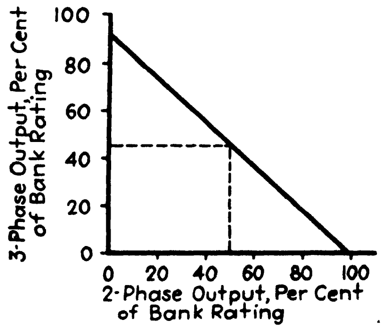


FIG. 135. Relation between two-phase output and three-phase output, Taylor connection.

The chief advantage of the Taylor connection is its ability to deliver both two-phase and three-phase power from the same set of four-wire mains. Its disadvantages, as compared with the Scott connection, are that three transformers are needed instead of two, that they are not alike, and that slightly more material is needed.

Fortescue Connection. The Fortescue connection for three-phase to two-phase transformation is shown in Fig. 136. Like the Taylor connection, it requires three single-phase transformers or a three-phase transformer with taps located in delta-connected windings. The taps are located so that the voltage AB is equal to the voltage CD and perpendicular to it, as shown in Fig. 136. The equivalent size of the transformer without a tap is 668 volt-amperes and of the other two transformers 748 volt-amperes. This makes the total equivalent transformer size 108.2 per cent of the output.

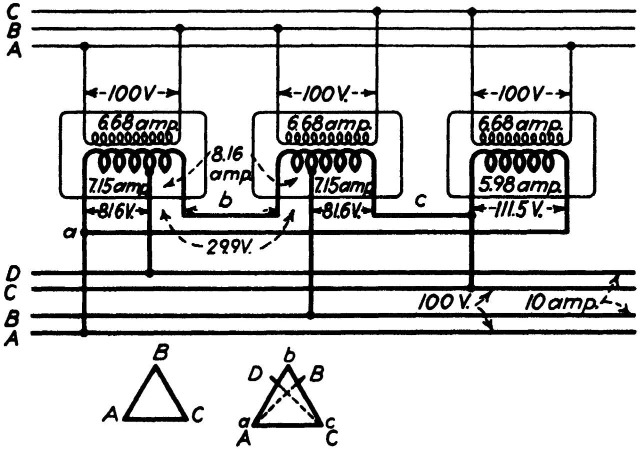


FIG. 136. Fortescue connection, three-phase to two-phase.

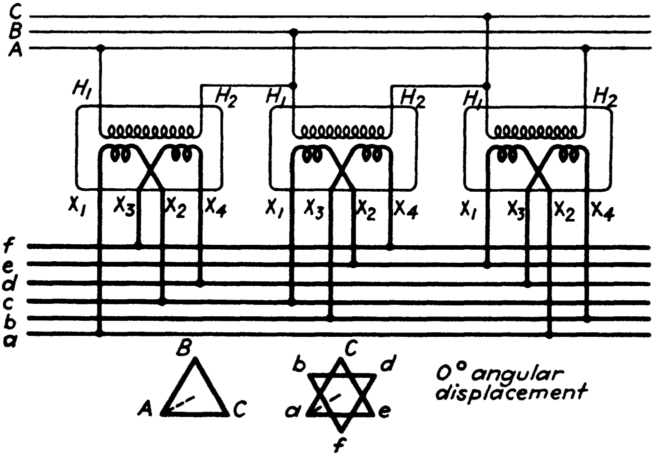


FIG. 137. Three-phase to six-phase, delta-double-delta.

SIX-PHASE CONNECTIONS

Many rotary converters are designed for six-phase alternating-current power, and this power can be derived from a two-phase circuit or more often from a three-phase circuit.

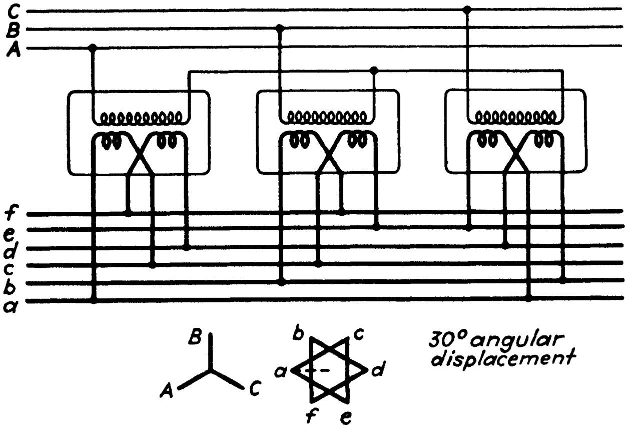


FIG. 138. Three-phase to six-phase, Y-double-delta.

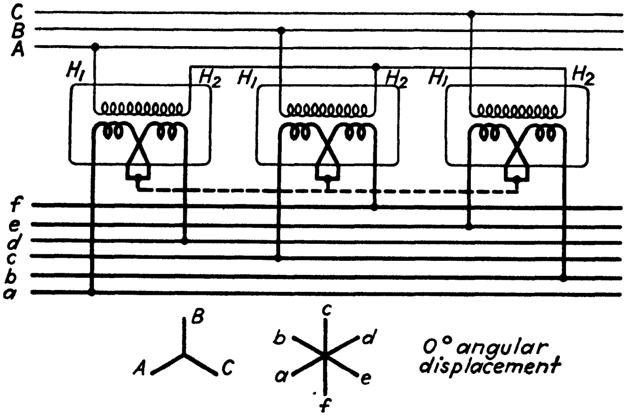


FIG. 139. Three-phase to six-phase, Y-double-Y.

Double Delta Connection. Figure 137 shows the arrangement for supplying power to a six-phase rotary from three transformers connected in delta on the high-voltage side. Each transformer has two independent low-voltage windings connected in two inde-

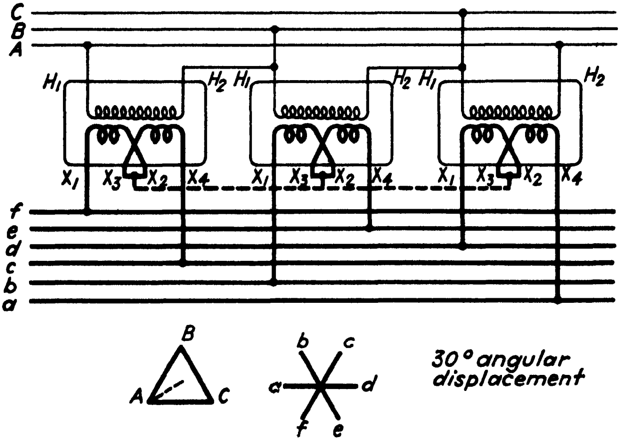


FIG. 140. Three-phase to six-phase, delta-double-Y.

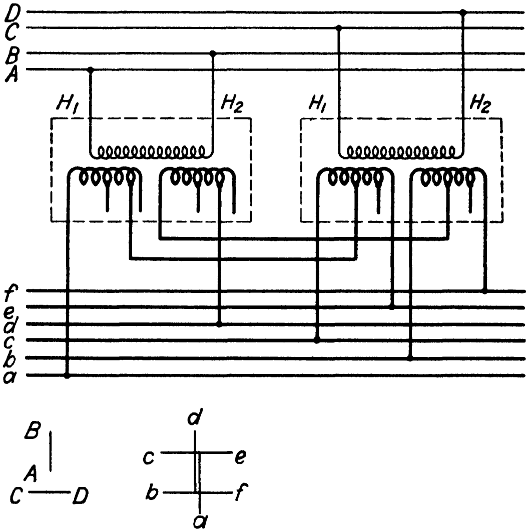


FIG. 141. Two-phase to six-phase.

pendent deltas 180 degrees from each other in phase, as shown. The rotary is fed from the points *abcdef*. Figure 138 is similar to Fig. 137 except that the high-voltage windings of the three transformers are connected in Y instead of in delta.

Double-Y Connection. Figures 139 and 140 show the double-Y connection of the low-voltage windings in the three transformers. Each transformer has either two low-voltage windings connected in series or else one low-voltage winding with a middle tap. If the three middle points are connected together, the junction forms a neutral point for the low-voltage system. It will also serve as the neutral, or middle, wire of a three-wire direct-current system fed from the rotary. Figure 139 shows the high-voltage windings in Y, and Fig. 140 shows them in delta.

Double Scott Connection. Figure 141 shows the connection for a six-phase rotary fed from a two-phase line. Each of the transformers has two independent secondaries with 50 and 86.6 per cent taps in each. They are connected to form two independent T's 180 degrees apart in phase, as shown. The vertical lines through *a* and *d* in the six-phase vector diagram really coincide. They are separated slightly in the sketch to make the construction clear.

Summary. If a single-phase load is to give a balanced load on a polyphase system, it is necessary to use a rotating machine between the load and the power supply. A polyphase system of any number of phases, however, may be derived from any other polyphase system.

CHAPTER XV

SPECIAL APPLICATIONS OF STANDARD TRANSFORMERS

Sometimes an emergency arises that makes it necessary to replace a transformer at short notice. If a transformer of the right rating is not at hand, some substitution must be made if possible, and it is important to know what kind of transformer can be used. In such a case efficiency is not important. The chief question is whether or not the transformer will stand up to the service. The answer to this depends on the losses in the transformer and on its insulation. It is therefore of interest to inquire if the normal losses of a transformer can safely be increased and what will be the effect on the losses of changing the voltage, frequency, or load of the transformer.

Transformer Losses. Transformer losses are of two kinds, iron losses and copper losses. *Iron loss* is the energy required to magnetize and demagnetize the iron. *Copper loss* is the energy consumed within the transformer to circulate current through the resistance of the windings. Copper loss can be separated into two parts: (1) that caused by the load current flowing in both the primary and secondary windings and (2) that due to the exciting current, occurring in the primary winding only. Normally, the copper loss caused by the exciting current is extremely small, but under abnormal conditions it may be important. Both iron loss and copper loss appear as heat in the transformer.

The iron loss in a transformer depends on the frequency of the circuit, the amount of iron in the transformer, and the density of magnetic flux in the iron. Flux density, in turn, depends on the voltage, frequency, area of cross section of the transformer core and the number of turns in the windings. The curves (Fig. 142) show how the iron loss varies with a change of flux density in a good grade of transformer iron; 100 per cent on the horizontal scale represents the flux density at which a typical 60-cycle distribution transformer might be run. It will be noted that for small ranges of flux density the iron loss varies almost as the square of the flux density. For example, an increase in flux density from 100 to 110 per cent results in an increase in the iron losses from 100 to about 125 per cent. At a given flux density the iron loss varies somewhat faster than the frequency. On 25 cycles at 100 per cent flux density the iron losses are only about 35 per cent of what they are for 60 cycles and the same flux density. The iron loss does not change with a change in the load on the transformer but remains constant as long as the primary voltage and frequency are not changed.

The energy in watts needed to circulate current through a resistance is the current squared multiplied by the resistance and is shown in the curve (Fig. 143). For example, 120 per cent of normal current corresponds to 144 per cent of normal copper loss.

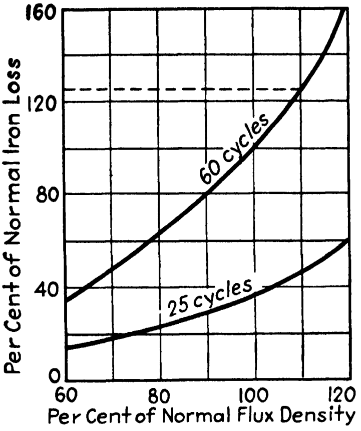


FIG. 142. Relation of iron loss to flux density.

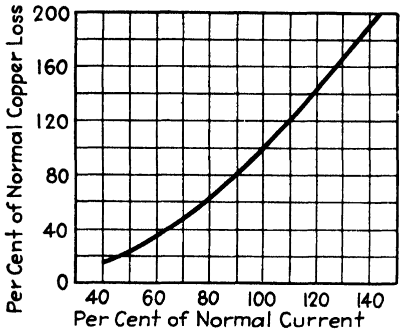


FIG. 143. Relation of copper loss to load current.

Temperature of the Windings. Copper loss appears as heat in the transformer windings. The oil in the transformer absorbs heat from the windings and transfers it to the cooling surfaces, where it is dissipated. When this process has begun, the temperature of the windings increases until a balance is reached where the rate at which heat is generated in the transformer just equals the rate at which it is absorbed by the oil and dissipated.

The final temperature that the coils will reach depends on four things:

1. On the rate at which heat is generated, *i.e.*, on the copper loss.

2. On the rate at which heat can be absorbed from the coils by the oil. The greater the area of coil surface exposed to the oil for a given copper loss the more rapid the transfer of heat and the smaller the difference in temperature between the copper and the oil.

3. On the rapidity with which the oil circulates. A transformer in oil of high viscosity will run hotter than in oil of low viscosity.

4. On the area and condition of the surface from which the heat is dissipated.

Temperature Limits. The American Standards limit the full-load *observable* temperature rise of a transformer winding with Class A* insulation to 55°C above the surrounding air, except that 60°C by thermometer is permissible for air-blast transformers and air-cooled reactors. The observable temperature is the maximum temperature that can be read on a thermometer placed against the coils or calculated from the rise of resistance of the coil. An allowance of 10° is made above this value for the difference in temperature between the hottest spots inside the winding and the observable temperature.

This rule is for the purpose of establishing the transformer rating. It does not prescribe the operating temperature at full load, but only the temperature rise. The danger in high temperatures lies in the possibility of damage to the insulation, and this depends on the actual temperature which the insulation reaches and not primarily on the temperature rise. It is evident, therefore, that a transformer operating in a low ambient temperature can safely carry more load than the same transformer in a high ambient temperature.

Recognizing this fact the American Standards include recommendations for the permissible loading of transformers by temperature. These are referred to in the chapter on Transformer Operation. They apply particularly to large transformers which are under constant supervision. Small distribution transformers and transformers in unattended substations should not be overloaded except in case of emergency. Although it is true that they can safely carry more load in cold weather than in hot, there is always the danger that an excessive load applied in the winter may not be decreased when summer comes and that the transformer may therefore be damaged.

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* Class A insulation consists of (1) cotton, silk, paper, and similar organic materials when either impregnated or immersed in a liquid dielectric; (2) molded and laminated materials with cellulose filler, phenolithic resins, and other resins of similar properties; (3) films and sheets of cellulose acetate and other cellulose derivatives of similar properties; and (4) varnishes (enamel) as applied to conductors.

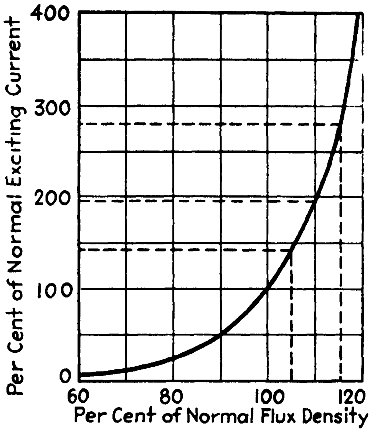

FIG. 144. Relation of exciting current to flux density.

Exciting Current. Another factor that may set a limit to the load on a transformer is the exciting current. This is the current in the primary winding which supplies the iron loss, plus an out-of-phase current which is required to magnetize the iron. A typical exciting-current curve is shown in Fig. 144. The exciting current increases with the flux density more rapidly than the iron loss, and for high flux densities the increase is much more rapid than for low flux densities. Referring to the curve, it will be seen that a 5 per cent increase in flux density above the point marked 100 per cent corresponds to an increase in the exciting current from 100 to about 140, a change of 40 per cent, whereas a 5 per cent increase above the 110 per cent point corresponds to an increase in the exciting current from about 190 to 280, an increase of 47 per cent.

For a given flux density the exciting current in amperes does not depend on the frequency, but the exciting volt-amperes do. The normal exciting current of a distribution transformer may be 2 to 5 per cent of the transformer's rated output and may have a power factor of 20 to 40 per cent. The exciting current, therefore, has little effect on the total current in the transformer, and its effect on the heating of the transformer is negligible under normal conditions where the flux density in the core is reasonably low. If the voltage is increased or the frequency decreased so as to magnetize the core above the knee of the magnetization curve, the exciting current may represent a considerable percentage of the full-load current and thus may increase the heating.

Insulation. Insulation is vital to the operation of a transformer. It must be strong and reliable, both electrically and mechanically, so as to stand up indefinitely against the conditions that it will meet in service. These conditions will probably include some jar and vibration and some abnormal voltages caused by accidents to the system, switching surges, and lightning disturbances.

Transformer insulation is designed to withstand safely the voltage of the circuit on which it is intended to be used. An ample factor of safety is allowed, but it is not expected that the transformer will be used much above its rated voltage. About 10 per cent above rated voltage is as much as its insulation should be expected to stand continuously.

CONNECTING TRANSFORMERS TO CIRCUITS OF OTHER THAN THEIR NORMAL VOLTAGE

A few general conclusions about connecting transformers to circuits of other than their normal voltage and frequency can now be drawn.

1. It is always safe to increase the frequency on a transformer at normal voltage. This causes a decrease in flux density and a decrease in iron loss and exciting current and improves the efficiency of the transformer. Since normal current can be carried, the kilovolt-ampere rating of the transformer need not be changed.

The reactance of the transformer will be increased with the frequency, and the regulation will therefore be poorer, especially at low power factors.

2. The frequency can be decreased if the voltage is decreased in the same proportion. This leaves the flux density the same and results in lower iron loss and exciting current on account of the lower frequency. The transformer is usually safe even if the iron loss and exciting current are increased slightly. For example, it is generally safe to use a 60-cycle transformer on a 25-cycle circuit if the voltage is half of normal. This means, of course, that the kilovolt-ampere output will be half of normal.

3. The voltage applied to a transformer can be decreased at normal frequency. With normal current this will decrease the kilovolt-ampere output approximately as the voltage.

4. The applied voltage should not be increased very much, regardless of frequency, on account of the insulation.

RECONNECTING TRANSFORMERS

The transformer applications considered thus far do not involve any change in connections inside the transformer case. Some transformers are arranged for a change in internal connections to adapt them to changed circuit conditions.

Most standard distribution transformers are built with a secondary winding in two parts, so that they can be connected in series or in parallel. This connection is usually made between the low-voltage leads outside the case. Some of the older types had their secondary winding in four parts and were provided with a terminal block where the coils could be connected in groups of two in series or two in parallel. With the series connection the secondary voltages were 440 and 220 and with the parallel connection 220 and 110 volts.

One such arrangement is shown in Figs. 145 and 146. The parallel coil connection is shown in Fig. 145, and the series coil connection in Fig. 146. With either connection the groups can be connected in series or in parallel by means of the four outlet leads.

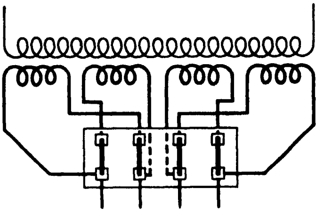

FIG. 145. Parallel connection of windings.

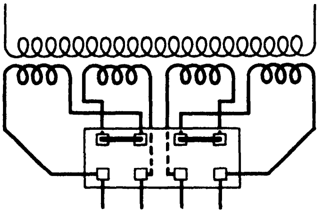

FIG. 146. Series connection of windings.

Some transformers also have taps or a series-parallel arrangement in their high-voltage windings. The diagram that accompanies the transformer always shows these connections and gives the necessary directions for making them.

If any reconnection of the transformer coils is considered outside those shown in the diagram, it should be undertaken only after careful investigation and usually only with the advice of the manufacturer. Otherwise, unexpected trouble may be encountered. For example, many core-form transformers are wound with half of the winding on each leg of the core, and a natural assumption would be that these two halves might be connected in parallel to adapt the transformer for half voltage. In many cases this assumption would be correct, and in other cases it might not be. If the transformer was designed for a high voltage, the ends of the high-voltage winding which are intended for connection to the line probably have special protection against impulses—either static plates or extra insulation or both. Now if the high-voltage winding is cut in two at the middle and connected in parallel, turns without this special protection can be connected directly to the line and may not be strong enough to stand the service.

Boosters. Standard transformers are sometimes used to boost the voltage of a long or overloaded line. The connection is shown in Fig. 147 for a distribution transformer of additive polarity. The high-voltage winding is connected across the line, and the low-voltage winding in series with the line so as to add its voltage to the line voltage. The size of transformer to be used for this purpose is found by multiplying the rated voltage of the transformer

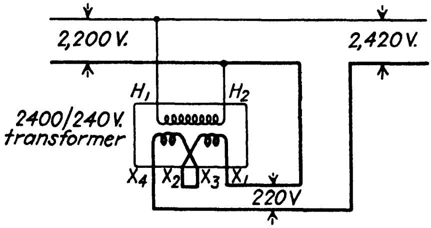

FIG. 147. Single-phase transformer used as a booster.

secondary by the maximum current to be carried in the line. For example, if it is desired to boost the voltage of a nominal 2,400-volt line by 10 per cent and the maximum current in the line is to be 100 amperes, a standard 2,400/240-volt distribution transformer might be used. The rating to be chosen would be 240 × 100 = 24,000 volt-amperes, or, say, a 25-kva transformer. It must be recognized, however, in this kind of use that the low-voltage winding of the transformer is being subjected to conditions for which it was not designed. The winding which was intended for connection to a 240-volt line is connected directly to a 2,400-volt line and is subjected to the surges which may occur on that line. The stress on the insulation between the high-voltage and the low-voltage windings is probably less than normal in some parts and greater than normal in others, and the voltage stress from the low-voltage winding to the core and case is much higher than normal unless the case is insulated from ground.

A similar use of single-phase transformers to boost the voltage of a three-phase, four-wire system is shown in Fig. 148. The principle is exactly the same as in Fig. 147.

Scott Connection. Another connection which is sometimes made as a special application of standard transformers is the three-phase to two-phase, or *Scott*, connection. This connection requires one transformer with a middle tap and one with an 86.6 per cent tap. For the latter a 90 per cent tap gives a fairly good approximation, and it is frequently proposed to use two standard transformers, one with a 90 per cent tap as the *teaser* and one with a middle tap as the *main*. Figure 149 shows the connection. The two-phase voltage will be slightly unbalanced, as indicated in the figure, but the two-phase load can be carried satisfactorily. It is necessary in this connection to choose for the main transformer one in which the

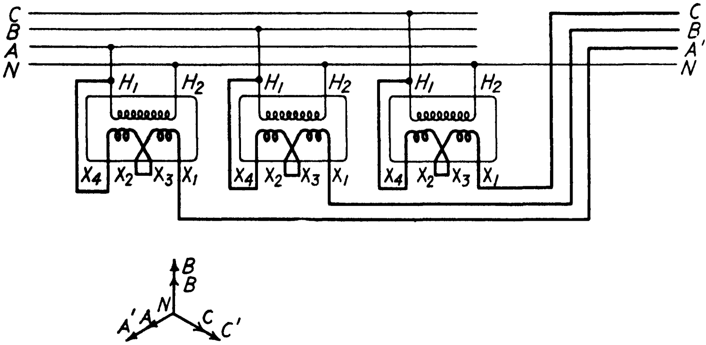

FIG. 148. Three single-phase transformers used to boost the voltage of a three-phase line.

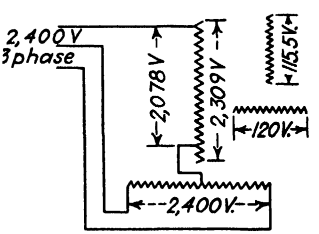

FIG. 149. Approximate Scott connection with standard transformers.

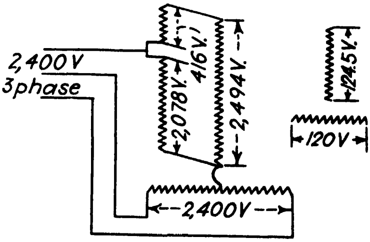

FIG. 150. Approximate Scott connection with standard transformers

two halves of the winding are well interlaced. Otherwise there will be a high reactance between the two halves. This will appear as reactance in the teaser circuit and may cause too high a regulation in that phase. For instance, many core-form transformers have two coils in series, one on each core. If a middle tap is taken out between the coils, a high reactance will be found.

Figure 150 is another approximate three-phase to two-phase connection, the main transformer having a middle tap. The teaser may or may not have taps. To bring up the voltage on the teaser transformer a small 5:1-ratio transformer is used as an autotransformer, as shown. This scheme also results in a small unbalance in the two-phase voltages. The size of the auxiliary transformer is determined by the fact that its voltage must be equal to the teaser voltage and its secondary winding must carry the teaser current.

In emergencies, standard transformers can often be used under conditions for which they were not designed, but in making such applications it is necessary to know what factors differ from normal and how these differences affect the transformer.

CHAPTER XVI

AUTOTRANSFORMERS

Autotransformers may be regarded as a special type of transformer in which the primary and secondary currents use a part of the winding in common. It is possible to connect any two-winding transformer as an autotransformer, although in many cases the transformer would not operate satisfactorily so connected because the insulation is not designed for such a condition.

Consider a transformer with a 1:1 ratio as shown in Fig. 151. The high-voltage rating is 100 volts at 10 amperes, the low-voltage rating is the same, and the transformer delivers 10 amperes at 100 volts to the load. Now connect H_2 and X_1 together as in Fig. 152, and connect a load to X_2 and H_1. With the same currents in the windings as before and with the same voltage on each winding, the transformer will deliver to the load 10 amperes at 200 volts. This is the principle of the autotransformer, and the example shows that for a 2:1 ratio the autotransformer can deliver twice as much power as a two-winding transformer of the same size.

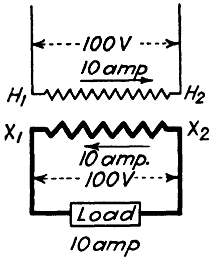

FIG. 151

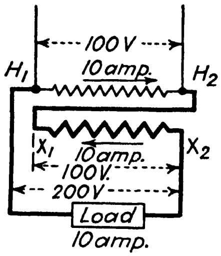

FIG. 152

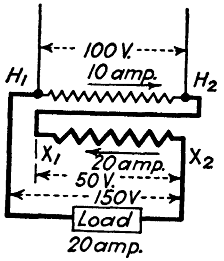

FIG. 153

FIG. 151. 1:1 transformer.
FIG. 152. 1:1 transformer connected as an autotransformer.
FIG. 153. 2:1 transformer connected as an autotransformer.

If a two-winding transformer is designed to transform from 100 volts to 50 volts and then connected as an autotransformer, as in

Fig. 153, the power delivered to the load will be 20 amperes at 150 volts, or three times the power delivered by the two-winding transformer. The economic advantage of the autotransformer, therefore, depends on the ratio of transformation.

Size of Parts. A convenient way to measure the advantage of an autotransformer over a corresponding two-winding transformer is to find the size of parts which it requires. By size of parts is meant the kilovolt-ampere rating of a two-winding transformer which could be built with the same active material as used in the autotransformer.

Let E_h = high voltage
E_l = low voltage
$R = E_h/E_l$ = ratio of transformation
P = output, kva
S = size of parts, kva

Then

$$S = P \times \frac{R-1}{R}$$

The fraction $\frac{R-1}{R}$ is evidently the size of parts required for an output of 1 kva with ratio R.

Figure 154 is a graph of the factor $\frac{R-1}{R}$ plotted against R. As an example of its use, suppose that 10 kva is to be transformed

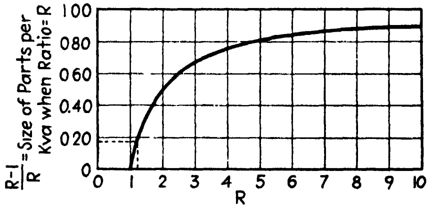

FIG. 154. Size of parts required for autotransformers.

from 110 to 90 volts. What size of parts would be required for an autotransformer?

$$R = {}^{110}\!/_{90} = 1.222$$

Finding on the graph (Fig. 154) 1.222 on the horizontal scale and following the dotted lines up to the curve and then to the scale at the left, it is found that $\frac{R-1}{R} = 0.182$, and the size of parts required will be $10 \times 0.182 = 1.82$ kva, or, say, 2-kva parts.

As the ratio increases, the advantage of the autotransformer over the two-winding transformer grows less, and autotransformers are rarely made with ratio greater than 4:1 or 5:1. Not only is the saving in material in an autotransformer of high ratio comparatively small, but the fact that the high-voltage and low-voltage windings are electrically connected requires, if the circuit is ungrounded, that both shall have the same insulation to ground. This would add considerably to the cost of an autotransformer for high ratio, and it is better to use a two-winding transformer for such applications.

Not only the size of parts but also the losses of an autotransformer are less than those of a corresponding two-winding transformer. For a given amount of material in the core and coils the loss will be nearly the same whether the material is made into a two-winding transformer or into an autotransformer. The higher output of the latter then results in a higher efficiency and a better regulation.

Use of Autotransformer. Autotransformers are applicable where (1) the ratio of transformation is not too great and (2) it is not necessary that the secondary circuit be electrically separated from the primary circuit. The reduced voltage used for starting alternating-current motors is almost always obtained from autotransformers. These are designed for short-time operation and are made as small as possible.

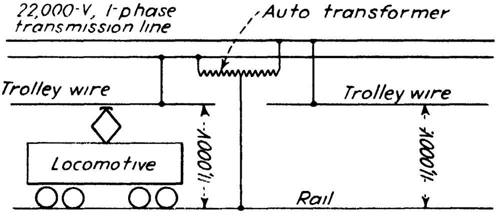

FIG. 155. Application of autotransformer to railway system.

An example of large and important autotransformers is found in an electrified railway system. Power is transmitted at 22,000 volts single phase, and autotransformers are connected across the line with their middle points grounded to the rails, as shown in Fig. 155.

This ensures that the voltage from the rails to each of the line wires will be the same, *i.e.*, 11,000 volts. The trolley wire is divided into sections which are insulated from each other, and alternate sections are fed from each side of the line, as shown in the sketch. The system thus has the advantage of 22,000-volt transmission and 11,000-volt utilization.

Another example of large autotransformers is at Los Angeles, where power from Hoover Dam is received at 275,000 volts and stepped down to 132,000 volts by means of two banks each consisting of three single-phase autotransformers rated at 65,000 kva each.

CHAPTER XVII

PHASE TRANSFORMATION BY AUTOTRANSFORMERS

Autotransformers are used on both single-phase and polyphase circuits, including circuits for phase transformation. One of the important questions to answer in applying autotransformers is the size of parts required, for this will largely determine the cost of the autotransformers. Formulas for the size of parts are given for each of the connections shown below.

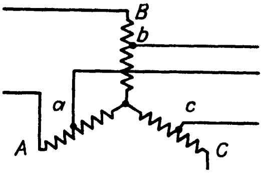

FIG. 156. Three-phase to three-phase, Y connection.

Three-phase to Three-phase, Y. Figure 156 shows three single-phase autotransformers connected in Y to decrease the voltage of a three-phase circuit. If the tap is in the middle of each autotransformer, the voltage on the low-voltage side will be half the voltage on the high-voltage side. With a balanced three-phase load each autotransformer operates as though it were on a single-phase circuit, and the total kilovolt-amperes of autotransformer rating is the same as the output. The size of parts is determined by the ratio

$$S = P \times \frac{R - 1}{R} \qquad (1)$$

where S = size of parts, kva
P = output, kva
R = ratio of high voltage to low voltage

This connection is similar to the Y-Y transformer connection in that it does not permit the triple-frequency component of the exciting current to flow. This causes voltage distortion unless the amount of power is small. If Y-connected autotransformers are to handle large amounts of power, each autotransformer is usually provided with an auxiliary winding. The three auxiliary windings are then connected in delta to provide a path for the triple-harmonic component of the exciting current. With three autotransformers connected in Y, the high-voltage neutral and the low-voltage neutral evidently coincide.

Three-phase to Three-phase, Open Delta. The open-delta or V connection of two autotransformers to reduce the voltage of a three-phase line is shown in Fig. 157. The neutral of the high-voltage circuit does not coincide with that of the low-voltage circuit, but the point of the V coincides. With the ratio and the load shown in Fig. 157 each autotransformer carries 5 amperes throughout its windings and has a voltage of 200. The autotransformer rating, therefore, is 5 × 200 = 1,000 volt-amperes each, and the corresponding size of parts is

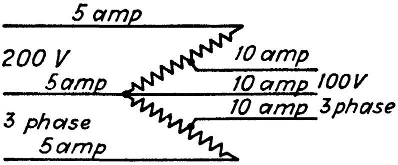

FIG. 157. Three-phase to three-phase, open-delta connection.

$$1{,}000 \times 0.5 = 500 \text{ volt-amperes each}$$

The power output from the bank is

$$10 \times 100 \times 1.732 = 1{,}732 \text{ volt-amperes}$$

and therefore the total parts are 2 × 500/1,732 = 0.577 of the output, instead of the 50 per cent which might be expected from the ratio. The difference is caused by the phase relation between the voltage and current and corresponds to that for the open-delta transformer connection. In general, the size of parts for each autotransformer in this connection is

$$S = \frac{P}{\sqrt{3}} \times \frac{R-1}{R} = 0.5774P \times \frac{R-1}{R} \qquad (2)$$

Example: What size of parts would be used for each of two autotransformers to transform 100 kva three-phase from 230 to 220 volts?

Solution: In this case $R = {}^{230}\!/_{220} = 1.045$

$$S = \frac{100}{\sqrt{3}} \times \frac{1.045 - 1}{1.045} = 2.49\text{-kva parts}$$

The total size of parts for the two autotransformers would be $2 \times 2.49 = 4.98$ kva.

Three-phase to Three-phase, T Connection. Figure 158 shows the T connection for two autotransformers to transform from three-phase to three-phase. In such a connection the autotransformer which is connected between two of the three-phase lines is usually referred to as the *main*, and the one connected from the middle of the main to the third line is called the *teaser*.

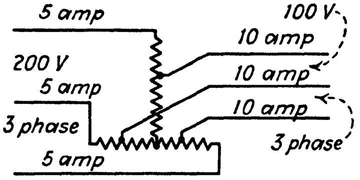

Fig. 158. Three-phase to three-phase, T connection.

With the ratio and load shown in Fig. 158 the output is 1.732 kva, the size of parts of the main autotransformer is $5 \times 200/2 =$ 500 volt-amperes, and the size of parts for the teaser is $\frac{5 \times 0.866 \times 200}{2} = 433$ volt-amperes.

In general,

$$\left.\begin{aligned} S_m &= \frac{P}{\sqrt{3}} \times \frac{R-1}{R} = 0.5774P \times \frac{R-1}{R} \\ \text{and} \qquad S_t &= \frac{P}{2} \times \frac{R-1}{R} \end{aligned}\right\} \qquad (3)$$

where S_m = size of parts for the main autotransformer

S_t = size of parts of the teaser

Solving the same example as above we find that the main takes 2.49-kva parts and the teaser 2.156-kva parts. This connection thus takes about 6.8 per cent smaller parts, total, than the open-delta connection. The two autotransformers are not duplicates, however, and the open delta is often preferred.

THREE-PHASE TO TWO-PHASE TRANSFORMATION

Three-phase to two-phase transformations can be made by autotransformers as well as by two-winding transformers if conditions of voltage ratio and of insulation are suitable. The same connection can be used to transform two-phase to three-phase, but this application is not so common, since most power systems are three-phase. The chief call for two-phase power is for the operation of two-phase motors.

In most two-phase motors the two windings are separate and insulated from each other. The two-phase voltages which feed such motors, therefore, need not necessarily have any particular relation to each other except that they must be equal and at right angles. They may have a common neutral, they may be connected together at some point other than the neutral, or they may be entirely separate, electrically. Some two-phase motors, however, especially those of old design, have their two circuits connected together. They require a supply in which the two phases either have a common neutral or else are entirely separate. Thus, need is found for transformers of different characteristics.

In this study let

$K = E_2/E_3$ = the ratio of the two-phase voltage to the three-phase voltage
P = total kva output from the bank of autotransformers
S_m = size of parts for the main
S_t = size of parts for the teaser

Three-phase Three Wire to Two-phase Four Wire. This is the well-known Scott connection and is probably more used than any other autotransformer connection for phase transformation. It is conveniently divided into three cases, according to whether the two-phase connections on the main and teaser lie inside or outside the three-phase connections.

Case I: When $K > 1$, *i.e.*, when the two-phase connections lie outside the three-phase connections on both main and teaser (see Fig. 159). The voltages and currents in the various parts of the winding are given below. The double subscript indicates the direction through the circuit; for instance, E_{1B} indicates the voltage from the point 1 in the diagram to the point B. The quantities E_2, I_2 and E_3, I_3 are the voltage and current in the two-phase circuit and in the three-phase circuit, respectively.

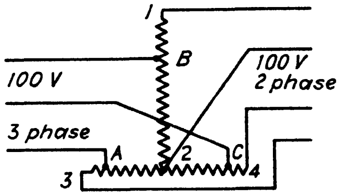

FIG. 159. Three-phase to two-phase, Case I.

$$\begin{aligned}
E_{12} &= E_2 & & \\
E_{B2} &= \frac{\sqrt{3}E_3}{2} & I_{B2} &= I_3 - I_2 \\
E_{1B} &= E_2 - \frac{\sqrt{3}E_3}{2} & I_{1B} &= I_2 \\
E_{3A} &= E_{C4} = \frac{E_2 - E_3}{2} & I_{3A} &= I_{C4} = I_2 \\
E_{A2} &= E_{2C} = \frac{E_3}{2} & I_{A2} &= I_{2C} = \sqrt{I_3^2 + I_2^2 - I_2 I_3 \sqrt{3}}
\end{aligned}$$

From these figures the size of parts can be calculated for the main and for the teaser by adding the volt-amperes in each part and dividing by 2. This gives

$$\left.\begin{aligned}
S_m &= \frac{P}{2} \times \frac{K - 1 + \sqrt{1 - 2K + \frac{4K^2}{3}}}{2K} \\
S_t &= \frac{P}{2} \times \frac{2K - \sqrt{3}}{2K}
\end{aligned}\right\} \qquad (4)$$

The limit of this case is when $K = 1$, *i.e.*, when the three-phase voltage equals the two-phase voltage, giving phase transformation without change in voltage. The expressions above then reduce to

$$S_m = 0.144P$$

and

$$S_t = 0.067P$$

Case II: When $1 > K > \sqrt{3}/2$, *i.e.*, K lies between 1 and 0.866. In this case the two-phase connection falls outside the three-phase on the teaser but inside on the main (see Fig. 160). The size of parts required is

$$S_m = \frac{P}{2}\left(\frac{1 - K}{\sqrt{3}} + \frac{\sqrt{1 - 2K + \frac{4K^2}{3}}}{2}\right)$$

and

$$S_t = \frac{P}{2} \times \frac{2K - \sqrt{3}}{2K} \qquad (5)$$

One limit of this case is $K = 1$, when the equations reduce to the same figures as before The other limit is $K = 0.866$, when the equations reduce to

$$S_m = 0.366P$$

and

$$S_t = 0,$$

which means that the teaser carries no current and is therefore unnecessary.

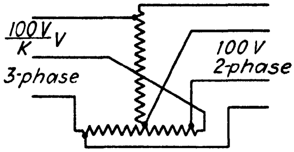

FIG. 160 Three-phase to two-phase, Case II.

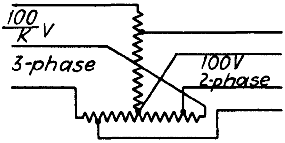

FIG. 161. Three-phase to two-phase, Case III.

Case III: When $\sqrt{3}/2 > K$. In this case the two-phase connections fall inside the three-phase connections on both main and teaser, as shown in Fig. 161, and it is found that

$$S_m = \frac{P}{2}\left(\frac{1-K}{\sqrt{3}} + \frac{\sqrt{1 - 2K + \frac{4K^2}{3}}}{2}\right)$$

and

$$S_t = \frac{P}{2}\left(1 - \frac{2K}{\sqrt{3}}\right) \tag{6}$$

It will be noted that the equations for S_t in Eqs. (4) and (5) are identical—also the equations for S_m in Eqs. (5) and (6). This is because Case II is a transition, in which the conditions in the teaser are the same as in Case I, whereas the conditions in the main are the same as in Case III.

Example: What size of parts would be needed for autotransformers to transform 50 kva from 200 volts three-phase to 220 volts two-phase?

Solution: $K = E_2/E_3 = {}^{220}\!/_{200} = 1.1$.

Here K is greater than 1, and the problem falls in Case I.

$$S_m = \frac{50}{2} \times \frac{1.1 - 1 + \sqrt{1 - 2 \times 1.1 + 1.33 \times 1.21}}{2 \times 1.1} = 8.44\text{-kva parts}$$

and

$$S_t = \frac{50}{2} \times \frac{2 \times 1.1 - 1.732}{2 \times 1.1} = 5.33\text{-kva parts}$$

Three-phase Three Wire to Two-phase Three Wire. In a two-phase three-wire circuit a common wire is used for one side of each of the two phases. A number of different locations for the common wire might be chosen. One scheme which is much used is to connect the common wire of the two phases to a point on the teaser and the other two wires to points on the main such that two voltages at right angles will be obtained, as indicated by the dotted lines in Fig. 162. This connection, like the former one, naturally divides into three cases.

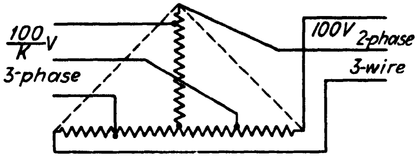

FIG. 162. Three-phase to two-phase, three-wire, Case I.

Case I: When $K > \sqrt{3}/2 \times \sqrt{2}$, *i.e.*, when K is greater than 1.225. Here all the two-phase connections fall outside the three-phase connections, as in Fig. 162, and

$$S_m = \frac{P}{2}\left(\frac{1}{\sqrt{2}} - \frac{1}{2K} + \sqrt{\frac{1}{4K^2} + \frac{1}{3} - \frac{\cos 15^\circ}{\sqrt{3}K}}\right)$$

or

$$\left.\begin{aligned} S_m &= \frac{P}{2}\left(0.707 - \frac{1}{2K} + \sqrt{\frac{0.25}{K^2} + 0.333 - \frac{0.5577}{K}}\right) \\ \text{and} \quad & \\ S_t &= \frac{P}{2}\left(1 - \frac{\sqrt{3}}{\sqrt{2}\,K}\right) = \frac{P}{2}\left(1 - \frac{1.225}{K}\right) \end{aligned}\right\} \tag{7}$$

Case II: When $\sqrt{3}/2 \times \sqrt{2} > K > \sqrt{2}/2$, *i.e.*, when K lies between 1.225 and 0.707. Here the two-phase tap on the teaser lies inside the three-phase tap, but the two-phase taps on the main lie outside the three-phase taps, as shown in Fig. 163. and

$$\left.\begin{aligned} S_m &= \frac{P}{2}\left(0.707 - \frac{1}{2K} + \sqrt{\frac{0.25}{K^2} + 0.333 - \frac{0.5577}{K}}\right) \\ &\text{which is the same as } S_m \text{ in Eq. (7), but} \\ S_t &= \frac{P}{2}\left(1 - \sqrt{\frac{2}{3}}K\right) = \frac{P}{2}(1 - 0.8165K) \end{aligned}\right\}\quad(8)$$

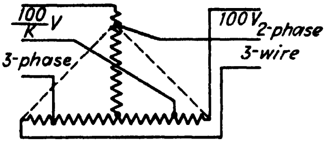

FIG. 163. Three-phase to two-phase, three-wire, Case II.

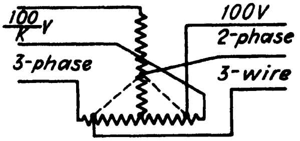

FIG. 164. Three-phase to two-phase, three-wire, Case III.

Case III: When $K < \sqrt{2}/2$, *i.e.*, when K is less than 0.707. Here all the two-phase taps lie inside the three-phase taps, as in Fig. 164, and

$$S_m = \frac{P}{2}\left(\frac{1}{\sqrt{3}} - \frac{\sqrt{2}K}{\sqrt{3}} + \frac{1}{\sqrt{2}}\sqrt{1 + \frac{4K^2}{3} - \frac{4K\cos 15°}{3}}\right)$$

or

$$\left.\begin{aligned} S_m &= \frac{P}{2}(0.5773 - 0.8165K + \sqrt{0.5 - 1.1154K + 0.667K^2}) \\ &\text{and} \\ S_t &= \frac{P}{2}(1 - 0.8165K) \end{aligned}\right\}\quad(9)$$

Example: What size of parts would be needed to transform 25 kva from three-phase to two-phase three wire, without change in voltage?

Solution: Here $E_2 = E_3$, whence $K = 1$, and the problem falls in Case II. Then

$$\begin{aligned} S_m &= \frac{25}{2}\left(0.707 - \frac{1}{2} + \sqrt{\frac{0.25}{1} + 0.3333 - \frac{0.558}{1}}\right) \\ &= 4.59\text{-kva parts} \end{aligned}$$

and

$$S_t = \frac{25}{2}(1 - 0.8165 \times 1) = 2.3\text{-kva parts}$$

Three-phase Three Wire to Two-phase Five Wire. For two-phase motors with interconnected windings it is necessary that two-phase power from autotransformers shall have a common neutral for the two phases, since they cannot be insulated from each other. This gives rise to the five-wire system. The autotransformers required are similar to those for the two-phase four-wire system except that the winding of the teaser is extended to cross the main, so that the junction of the two becomes the neutral of the two-phase system as shown in Fig. 165. Four cases may be distinguished.

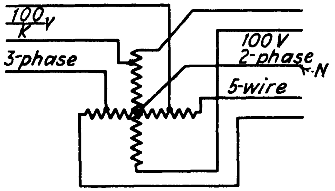

FIG. 165. Three-phase to two-phase, five-wire, Case I.

Case I: When $K > \sqrt{3}$, *i.e.*, K is greater than 1.732, and the two-phase connections lie outside the three-phase connections on both main and teaser.

$$\left.\begin{aligned} S_m &= \frac{P}{2}\left(\frac{1}{2} - \frac{1}{2K} + \sqrt{\frac{1}{3} - \frac{1}{2K} + \frac{1}{4K^2}}\right) \\ &= \frac{P}{2}\left(\frac{K - 1 + \sqrt{1 - 2K + \frac{4K^2}{3}}}{2K}\right) \\ \text{and} \qquad S_t &= \frac{P}{2}\left(1 - \frac{\sqrt{3}}{2K}\right) = \frac{P}{2}\left(1 - \frac{0.866}{K}\right) \end{aligned}\right\} \qquad (10)$$

This case is illustrated in Fig. 165.

Case II: When $\sqrt{3} > K > 1$, *i.e.*, when K lies between 1.732 and 1.

$$\left.\begin{aligned} S_m &= \text{same as } S_m \text{ in Case I, above} \\ S_t &= \frac{P}{4} \end{aligned}\right\} \qquad (11)$$

Case III: When $1 > K > \sqrt{3}/2$, *i.e.*, when K lies between 1 and 0.866.

$$\left.\begin{aligned} S_m &= \frac{P}{2}\left(\frac{1-K}{\sqrt{3}} + \frac{1}{2}\sqrt{1 - 2K + \frac{4K^2}{3}}\right) \\ &\text{and} \\ S_t &= \frac{P}{4} \end{aligned}\right\} \qquad (12)$$

Case IV: When $\sqrt{3}/2 > K$, *i.e.*, when K is less than 0.866.

$$\left.\begin{aligned} S_m &= \text{same as } S_m \text{ in Case III above} \\ &\text{and} \\ S_t &= \frac{P}{2}\left(1 - \frac{K}{\sqrt{3}}\right) = \frac{P}{2}(1 - 0.5774K) \end{aligned}\right\} \qquad (13)$$

Three-phase to Six-phase Transformation. Sometimes six-phase synchronous converters are operated from three-phase lines by means of autotransformers. The connection is shown in Fig. 166. The three autotransformers are connected in Y, and each has

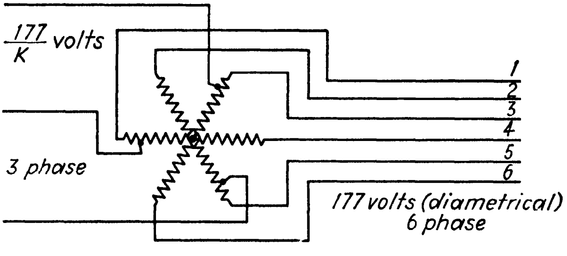

FIG. 166. Three-phase to six-phase by autotransformers.

an extended winding so that the common point of the three autotransformers is also the neutral point of the synchronous converter, as shown. In this connection the extended windings of the autotransformers together with the windings of the machine form a path in which the third-harmonic component of the exciting current can flow. The voltage, therefore, is not distorted from this cause as it is in the case of Y-connected three-phase transformers or autotransformers. With the connection shown in Fig. 166 the synchronous converter may be connected to a three-wire direct-current system, the middle or neutral direct-current line being connected to the common point of the autotransformers.

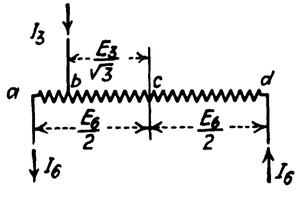

FIG. 167. Single autotransformer for three-phase to six-phase.

To calculate the size of parts needed for each autotransformer,
let E_3 = voltage between the three-phase lines
E_6 = alternating-current voltage of the converter (diametrical)
$K = E_6/E_3$

and consider one of the autotransformers as shown in Fig. 167, with the three-phase tap, *b*, inside the six-phase tap, *a*. Call this condition

Case I: When $K > 2/\sqrt{3}$, *i.e.*, K is greater than 1.155.

Then the voltage from *a* to *b* is $\frac{E_6}{2} - \frac{E_3}{\sqrt{3}}$

from *b* to *c* is $\frac{E_3}{\sqrt{3}}$

from *c* to *d* is $\frac{E_6}{2}$

The corresponding currents are respectively I_6, $I_3 - I_6$, and I_6 and the size of parts for each autotransformer is

$$S_a = \frac{1}{2}\left[\left(\frac{E_6}{2} - \frac{E_3}{\sqrt{3}}\right) I_6 + \frac{E_3}{\sqrt{3}}(I_3 - I_6) + \frac{E_6}{2} I_6\right]$$

or

$$S_a = \frac{P}{3}\left(1 - \frac{1}{\sqrt{3}K}\right) = \frac{P}{3}\left(1 - \frac{0.5774}{K}\right) \qquad (14)$$

If the three-phase connection lies outside the six-phase connection, two other cases may be distinguished, depending on whether the three-phase current or the six-phase current is the greater.

Case II: When $2/\sqrt{3} > K > 1/\sqrt{3}$, *i.e.*, when K lies between 1.155 and 0.5774.

$$S_a = \frac{P}{6} \qquad (15)$$

Case III: When $1/\sqrt{3} > K$, or K is less than 0.5774.

$$S_a = \frac{P}{3}\left(1 - \frac{\sqrt{3}K}{2}\right) = \frac{P}{3}(1 - 0.866K) \qquad (16)$$

Example: What size of parts is needed for autotransformers to run a 100-kilowatt 250-volt 60-cycle six-phase synchronous converter from a three-phase 230-volt line? The converter alternating-current voltage is 177, and the current per terminal is 200 amperes.

Solution: $K = {}^{177}\!/_{230} = 0.77$, which lies between 0.5774 and 1.155 and indicates that Case II should be used.

$$S_a = {}^{100}\!/_{6} = 16.67\text{-kva parts for each autotransformer}$$

Autotransformers have a broad field of usefulness and can be used to advantage in many single-phase and polyphase circuits. Where they are suitable, their use is economical both in cost and in losses. They are not advantageous for large ratios of transformation, and care must always be taken to avoid trouble from the fact that the primary and secondary circuits are electrically connected.

CHAPTER XVIII

CONSTANT-CURRENT-REGULATING TRANSFORMERS

Modern street lighting is done largely by means of high-efficiency incandescent lamps, connected in series and supplied with alternating current from some sort of regulating device. Such lamps for the best operation require that the current supplied to them be kept very close to its normal value. If the current falls below normal, the light decreases more than proportionally, and if the current rises above normal, the life of the lamp is shortened. The regulating device, therefore, must be able to take energy from a constant-voltage alternating-current system and deliver it to the lamps at a constant current.

The best device now available for such service is the constant-current-regulating transformer. This is a transformer in which the primary and secondary coils are movable with respect to each other. The coils automatically take the right position to deliver rated current to the lamp circuit.

Station Type. Constant-current-regulating transformers may take one of several mechanical forms One of the earlier types of mechanism is shown in Fig. 168. The openings, or windows, in the core are much longer than would be necessary to take the coils. The stationary coil is located at the bottom of the windows, and the movable coil is suspended above it by means of pulleys and a counterweight. An expanded metal case surrounds the transformer to protect the coils and allow free ventilation. This type is used in substations where it can be set level on a solid foundation so as to avoid any possibility of friction between the moving coil and the core. It is called the *station type.* It has been much used in the past and is still used in considerable numbers.

Pole Type. Some years ago a demand arose for a constant-current-regulating transformer which could be mounted on a pole and which would operate without attention for long periods. This led to the development of the pole-type constant-current-regulating transformer. The requirements of this type as to regulation are just as strict as those for the station type. In addition it must be able to operate with the required regulation even if it is not perfectly level. It follows that the movable coil cannot be freely suspended, as in the station type, but must be guided throughout its travel so that friction will not interfere with its free movement.

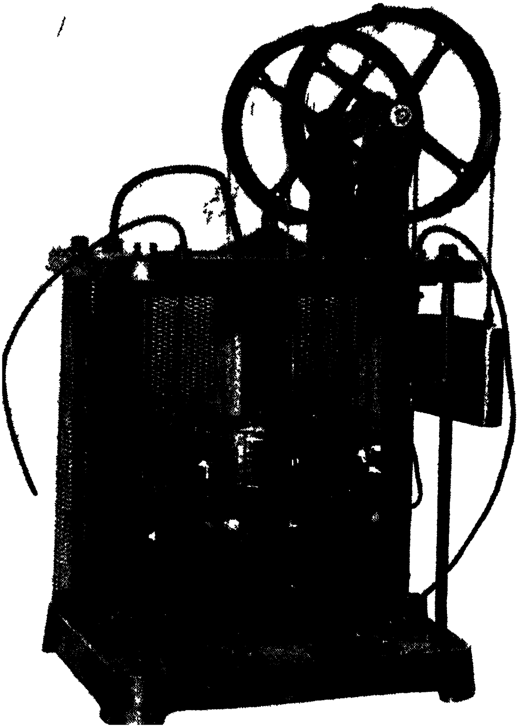

FIG. 168. Constant-current-regulating transformer, station type.

Two types of mechanism are in use for pole-type regulators. The first supports the movable coil in a cradle which is hinged at one end to brackets on the frame and is supported at the other end from a lever which carries the counterweight. Figure 169 is an example of this construction. A later development uses a parallel-motion device to guide the movable coil as shown in Fig. 170. The coil cradle is supported at one end by vertical members which are rigidly attached to the cradle. The upper ends of the vertical

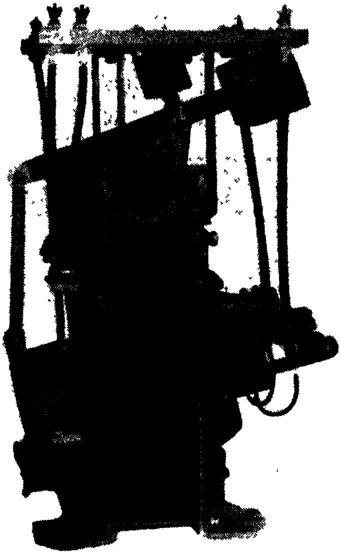

FIG. 169. Pole-type constant-current-regulating transformer, with hinged coil.

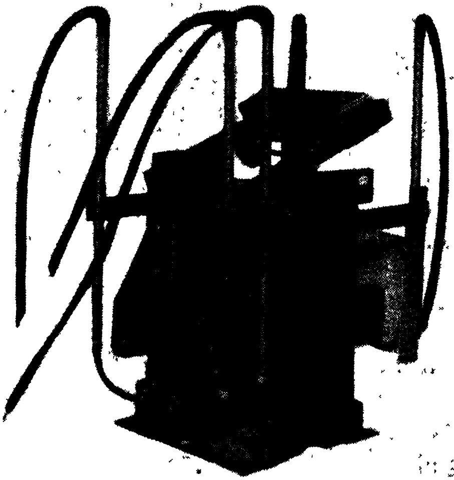

FIG. 170. Pole-type constant-current-regulating transformer, with parallel motion mechanism.

members are carried on ball bearings by the lever which carries the counterweight, and the travel of the lower end is guided by the links shown in the figure. The four pivot points form a parallelogram, and the moving coil, therefore, remains parallel to the stationary coil throughout its travel. This mechanism gives excellent current regulation.

Manhole or Subway Type. Sometimes constant-current-regulating transformers are needed for operation in a vault where they are liable to be submerged. For such a case a *manhole*, or *subway*, type has been produced. It is similar to the pole type in its coils and mechanism, but it is mounted in a watertight tank which is provided with wiping nipples to receive lead-covered cables. Figure 171 shows the general appearance.

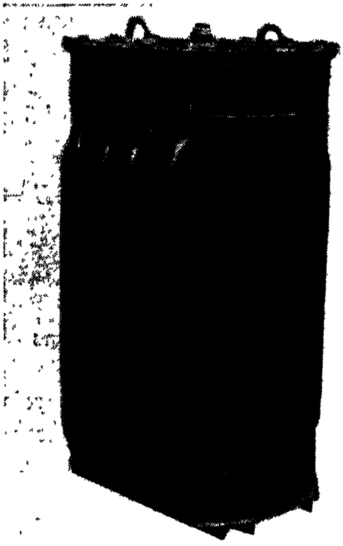

Fig. 171. Manhole or subway tank for constant-current-regulating transformer.

Principle of Operation. The operation of constant-current-regulating transformers can be understood with the help of Fig. 172. The sketch shows a station type regulator, but the explanation applies as well to the pole type or the manhole type.

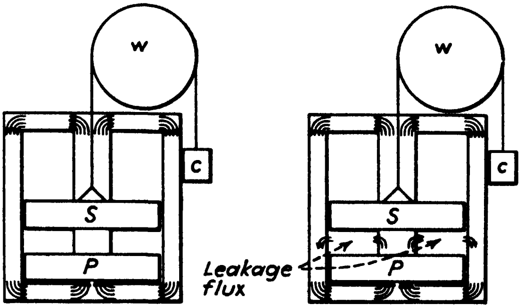

Fig. 172. Flux and magnetic circuits.

In Fig. 172, P is the primary coil, S is the secondary coil, W is the wheel or lever arrangement used to suspend the moving coil, and C is the counterweight. Suppose now that a voltage is applied to P while the circuit of S is open. An exciting current will flow, and a magnetic flux will be induced through the primary coil and up the middle leg of the iron to the top. Here the total flux will divide, and half will return down each of the outer legs to the primary coil. The amount of flux through P is determined from the usual transformer formula

$$E = kfANB$$

where E = voltage
k = a constant
A = area of core
N = number of turns
B = flux density
f = frequency in cycles per second

The flux in the iron induces a voltage in the secondary coil, and if the circuit is completed (*e.g.*, through a series of lamps), a current will flow. The current in S sets up a magnetomotive force opposed to that of P, and a part of the magnetic flux through P will be forced across the opening between P and S instead of following the iron circuit. This has two results. (1) The voltage in S will be reduced on account of the reduced flux which links it, and (2) there will be an electromagnetic force on S tending to raise it. This force is caused by the reaction of the leakage flux on the current in S. The counterweight is normally adjusted so that the weight of the coil is just equal to the counterweight plus the electromagnetic force when the coil is carrying the desired current.

If a part of the load is suddenly short circuited, there will be an instantaneous rise in the secondary current and consequently in the leakage flux. This results in an increased force between coils, and the secondary coil moves upward. The leakage space between the coils is thus increased, and the secondary voltage is diminished to a point where it will again send only the desired current through the decreased resistance of the circuit.

The relation of the various quantities is shown by the vector diagram (Fig. 173). For the sake of simplicity the losses in the regulator are neglected and it is assumed that the secondary load has a power factor of 100 per cent. If OE_p is the voltage applied to the primary coil, OF will be the flux which links this coil. OE_s, exactly opposite to OE_p, would be the voltage induced in the secondary if there were no magnetic leakage, *i.e.*, if the secondary coil were open circuited. At full load on the secondary there will be a normal leakage between primary and secondary of 40 per cent of the primary flux, more or less, and since this leakage flux is in phase with the secondary current, it will be perpendicular to the flux through the secondary coil which produces the secondary voltage. Therefore, on OF as a hypotenuse construct a right triangle with one side equal to 40 per cent of OF and the other side equal to $\sqrt{100^2 - 40^2} =$ 91.6 per cent of OF. OF_s is the flux which induces the secondary voltage, and it leads the secondary voltage by 90 degrees. The secondary voltage delivered to the load then is OE_2 and the secondary current will be in phase with OE_2, since the load power factor is 100 per cent.

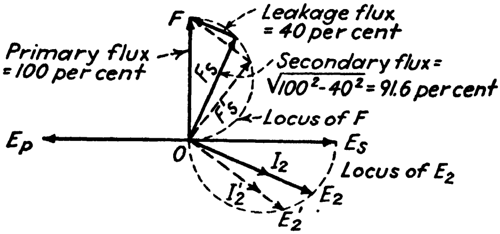
F
Leakage flux = 40 per cent
Primary flux = 100 per cent
Fs
Secondary flux = √100²-40² = 91.6 per cent
F's
Locus of F
Ep
O
Es
I2
Locus of E2
I'2
E2
E'2

FIG. 173. Vector relations of voltage and flux.

If a part of the load is short circuited, the coils will move apart as explained above. This will cause the vectors to take the position shown by the dotted lines, increasing the leakage flux and decreasing the flux through the secondary coil with a consequent reduction of the secondary voltage. The secondary current is thus brought back to its normal value. Constant-current-regulating transformers are usually designed so that, with normal voltage and frequency on the primary and with the secondary short circuited, normal secondary current will not quite cause full separation of the coils.

It is interesting to trace the effect of a change in the primary voltage or frequency when the secondary load is not changed. An increase in the primary voltage will cause an increase in the primary flux. Since the secondary flux must remain the same for the same load, the coils must move apart so as to increase the percentage of leakage. This lowers the primary power factor. It may also cause an increase in the short-circuit current of the secondary coil if the moving coil reaches the top of the opening.

An increase in the primary frequency, without a corresponding change in voltage, will decrease the primary flux. The secondary flux must decrease in the same proportion. The leakage flux also must decrease in the same proportion, and the coils therefore must move closer together. The frequency can be varied only within rather narrow limits without changing the voltage. If it becomes too low, the magnetic density in the iron becomes too high. If the frequency is too high, the percentage of leakage becomes high and the regulator has reduced capacity and poor power factor.

It is possible, however, to operate a 60-cycle regulator on 25 cycles or vice versa if the primary voltage and secondary load are properly adjusted. It was shown above that the leakage flux is determined by the ampere turns and the distance between coils. If the coils keep their normal position, therefore, the amount of leakage is independent of the frequency. Then the primary also must have the same flux regardless of frequency in order that the percentage of leakage shall be the same. It follows that the primary voltage must be changed in proportion to the frequency, and the secondary voltage and output will change in the same ratio. For example, a 2,400-volt 60-cycle 24-kilowatt regulator will operate as a 1,000-volt 25-cycle 10-kilowatt regulator, and the magnetic densities will be the same in all parts of the magnetic circuit. In using a regulator on a circuit of higher frequency than that for which it was designed, it is necessary to be sure that the insulation is suitable for the higher voltages.

The primary and secondary windings of constant-current-regulating transformers are often provided with taps, and from what has gone before, it will be easy to see the effect of using the taps. If a 2,200-volt circuit is connected to the 2,400-volt tap on the regulator, the volts per turn and consequently the flux through the primary coil will be decreased. For any given output therefore, the coils will be closer together, the leakage will be less, and the power factor will be higher. If 2,200 volts is connected to the 2,000-volt tap, the effect will be the reverse. For a given output the coils will be farther apart, and if the secondary is short circuited, there may be a rise of current because the coils may not be able to move far enough apart to cause the total flux to leak with normal current.

The tap in the secondary has a somewhat different effect. If the secondary load is connected to the tap, the ampere turns of the secondary are decreased. This will decrease the leakage flux and consequently increase the flux through the secondary coil, but this increased flux will link with a smaller number of secondary turns, and the secondary voltage will be lowered. If the regulator is short circuited, there will be a rise of current in the secondary to give the normal ampere turns. This connection is useful to raise the primary power factor if the regulator is to be used for a long time with a light load. It is rarely worth while to change connections for temporary load changes, because the regulator can take care of such conditions by a movement of the coil. The counterweight must be adjusted whenever the secondary connection is changed.

The current regulation of a constant-current-regulating transformer is very good. The moving parts are supported on ball bearings, and the current should not vary more than about 1 per cent from its rated value.

Constant-current-regulating transformers differ in several important respects from the usual power and distribution transformers. Their load is a series of lamps in which the current is constant. Increased load, therefore, means increased resistance in the secondary circuit and consequently increased voltage delivered by the secondary. It is impossible to overload a constant-current-regulating transformer. As load is added, *i.e.*, as the secondary resistance is increased, the coils come closer and closer together. When the moving coil has reached the limit of its travel toward the stationary coil, the maximum voltage is being delivered. If still more resistance is added to the secondary circuit, the secondary current must decrease.

Power and distribution transformers reach their maximum temperature at maximum load, but constant-current-regulating transformers reach their maximum temperature at zero load, *i.e.*, short-circuited secondary. Since the currents in the windings of these transformers are the same for all conditions of load, the I^2R losses are the same, and since the applied voltage is the same, the iron loss in the core is practically constant.* But the leakage flux between the coils cuts the end frames and other mechanical parts and also sets up a cross flux in the core. These effects increase as the coils separate, with the result that maximum temperature is reached at maximum coil separation.

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* As the coils separate, the total amount of leakage flux between the coils increases, and this decreases the flux in the top part of the core. The iron loss in the core is therefore somewhat less at full separation of the coils than at minimum separation.

Monocyclic Square. If reactors and capacitors of the proper characteristics are connected in a square, as shown in Fig. 174, a constant voltage applied at the points A and C will cause a constant current to flow through a load connected to the points B and D regardless of the impedance of the load within the capacity of the apparatus.* Such a circuit is known as a monocyclic square. It has been used only to a limited extent for street lighting, because any change in the voltage applied to the square causes a corresponding change in the current. The moving-coil type of constant-current-regulating transformer is therefore preferable for street lighting.

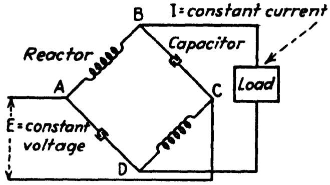

FIG. 174. Monocyclic square.

For airport lighting, however, it is necessary to adjust the illumination for different conditions of weather and service, and lighting systems based on the monocyclic square have found considerable application.

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* See Steinmetz, "Theory and Calculation of Electric Circuits," McGraw-Hill Book Company, Inc., New York, 1917.

CHAPTER XIX

INSTRUMENT TRANSFORMERS

Modern power systems depend for their success on transmitting and distributing power at voltages much higher than the voltages which are desirable for use. Such systems would be impracticable, however, if it were not possible to measure and control the power and to guard the high-voltage lines against abnormal conditions. On the other hand, excellent meters, instruments, and relays are available for measuring power and for protecting and controlling the systems, but they are all designed for operation on low-voltage circuits. The connecting link between these two conflicting requirements—high voltage for the lines and low voltage for the meters—is supplied by instrument transformers, which deliver to the meters and relays a small-scale, low-voltage reproduction of what is going on in the power circuits.

Polarity. In using instrument transformers with various instruments and relays it is necessary to know the relative polarity of the primary and secondary windings, *i.e.*, the relative instantaneous direction of current in the leads. This is indicated by marking one terminal of each winding either with a white polarity marker or with the letters H_1 and X_1 for the high-voltage winding and the low-voltage winding, respectively. The marked leads are of the same polarity. At the instant when current flows toward the transformer in the marked primary lead, current will tend to flow away from the transformer in the marked secondary lead, and vice versa.

Burden. The word *burden* is generally used for the load of instruments, relays, wiring, etc., connected to the secondary circuit of instrument transformers. This distinguishes it from the *load* in the main circuit which is to be measured or controlled.

CLASSES OF INSTRUMENT TRANSFORMERS

Instrument transformers are of two general classes, voltage transformers, or potential transformers, and current transformers. A potential transformer is similar to a power or distribution transformer except that it is designed for a small output and for a very small regulation and is then *compensated* to give its exact ratio at some specified burden. Compensation is the adjustment of the turn ratio to compensate for the voltage drop in the transformer at the specified burden. Current transformers are designed for connection in series with the line whose current is to be measured. They are governed by the same laws which govern all transformers, but the factors which are most important in current transformer design are less important in voltage transformers. This results in a difference in operation as well as in appearance. Current transformers as well as voltage transformers are compensated for a specified burden.

Both potential transformers and current transformers are made dry or gum filled for voltages of 13,800 and below, and dry current transformers are made for 23,000-volt circuits. For higher voltages most instrument transformers are oil insulated, and sometimes special conditions call for oil-insulated transformers for lower voltages.

Potential Transformers. In the ideal potential transformer the secondary voltage would always be the exact fraction of the primary voltage indicated by the name-plate ratio and would always be exactly 180 degrees from the primary voltage in phase. Actually it is impossible to keep this exact relation for all conditions of burden. Iron loss, copper loss, and magnetic leakage between the coils of the transformer cause a small change in the ratio of the transformer as the burden changes. They also cause a small shift in the phase position of the secondary voltage with respect to the primary voltage. This *phase angle* is of no importance in instruments which measure voltage only, such as voltmeters and certain relays, but for wattmeters it may be a considerable factor. In good potential transformers both the ratio error and the phase angle are very small, and they can usually be neglected in commercial measurements. Figure 175 shows ratio and phase-angle curves for a typical potential transformer for various burdens.

Potential transformers are used with voltmeters, wattmeters, watt-hour meters, relays, etc. Several instruments may be connected to the same transformer if their sum does not exceed the burden for which the transformer was designed. Some of the connections commonly used for potential transformers are shown in

Figs. 176 and 177 together with the vector relations of the voltages. Figure 178 illustrates typical low-voltage potential transformers. The white bushing indicates polarity. Figure 179 shows a high-voltage oil-insulated potential transformer. Polarity is shown by the porcelain button on top of the case.

Current Transformers. In a perfect current transformer the

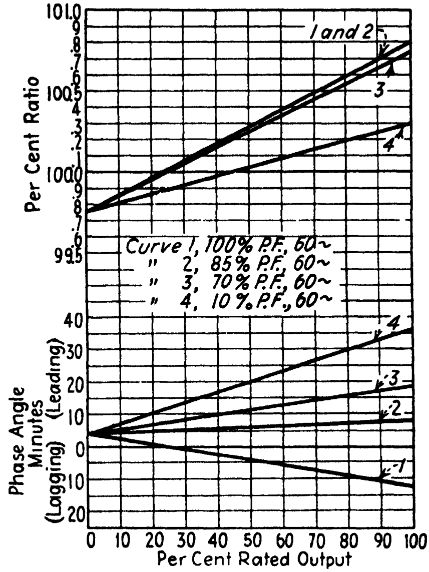
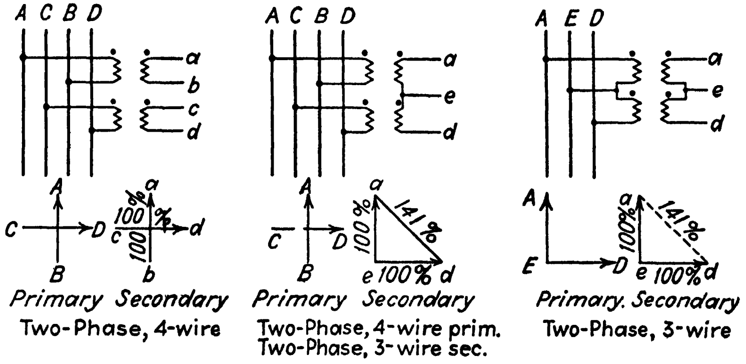


FIG. 175. Typical ratio and phase-angle curves, potential transformer.



Primary Secondary
Two-Phase, 4-wire

Primary Secondary
Two-Phase, 4-wire prim.
Two-Phase, 3-wire sec.

Primary. Secondary
Two-Phase, 3-wire

FIG. 176. Two-phase groupings of potential transformers, showing connections and voltage vectors.

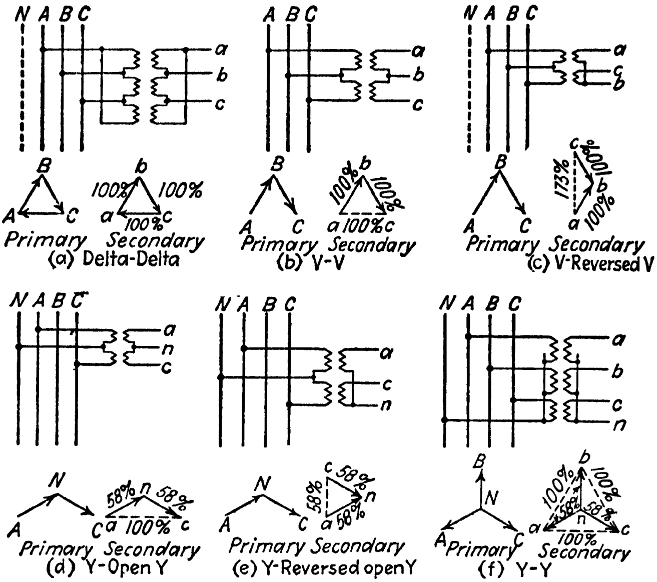


FIG. 177. Three-phase groupings of voltage transformers, showing connections and voltage vectors.

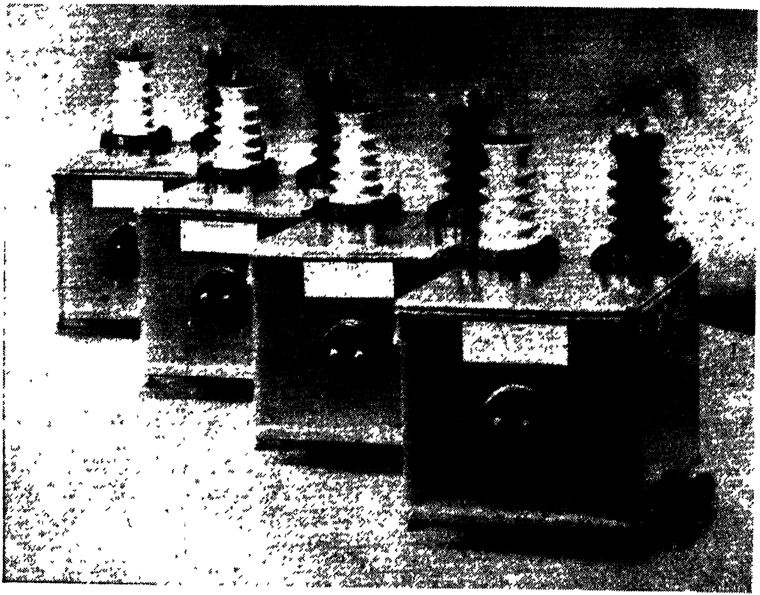


FIG. 178. Small-potential transformers.

secondary current would be proportional to the primary current and 180 degrees from it in phase regardless of the amount of primary current or of secondary burden. In an actual current transformer, however, this is not the case. Every core material thus far discovered takes a certain number of ampere turns to induce in it the magnetic flux which, in turn, causes the secondary voltage. The secondary ampere turns, therefore, are the vector difference between the primary ampere turns and the exciting ampere turns. As the burden is changed, the secondary voltage must change with it to send the same current through the changed impedance. The secondary voltage also changes with a change in the primary current, since a different voltage will be required to send the changed current through the same burden. And with each change in secondary voltage the magnetic flux in the core and consequently the exciting current must change. Both ratio and phase angle of a current transformer, therefore, vary with the primary current and with the secondary burden. Figure 180 shows typical performance curves. The errors are so small that they are usually neglected for commercial measurements. Correction can be made, however, and this is sometimes necessary for accurate laboratory work.

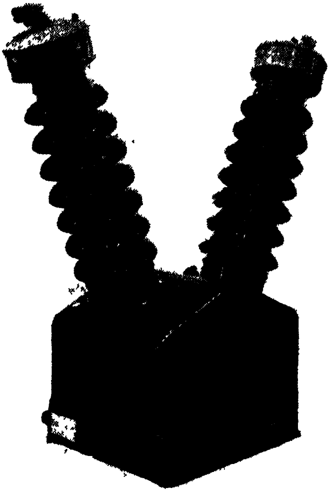


FIG. 179. Oil-insulated potential transformer for 66,000-volt circuit.

Figures 181 and 182 show connections frequently used for current transformers, with the corresponding vector diagrams. The arrows in the sketches of connections show the assumed positive direction of currents in the circuits, and the figures on the vectors show the amperes in various parts of the circuit, assuming that the secondary of each current transformer delivers 5 amperes. Figure 183 shows a typical current transformer for low-voltage circuits.

If oil-insulated current transformers for high-voltage circuits are mounted in metal tanks, with high-voltage bushings for the high-voltage leads, a tall and relatively heavy unit results (see Fig. 184). Sometimes this height is desirable because it brings

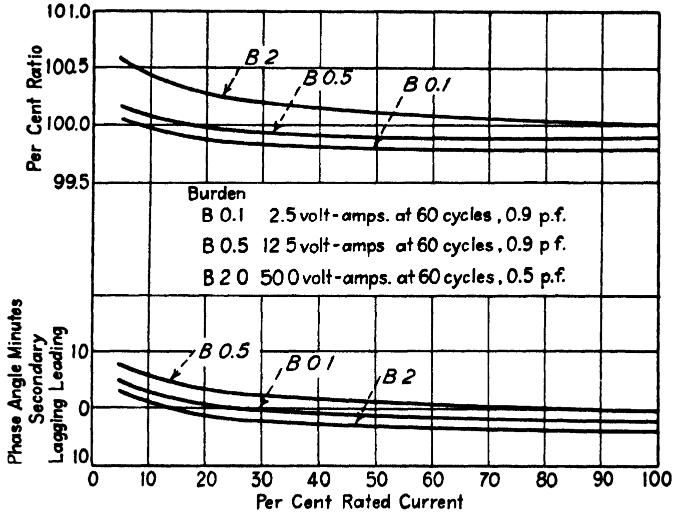
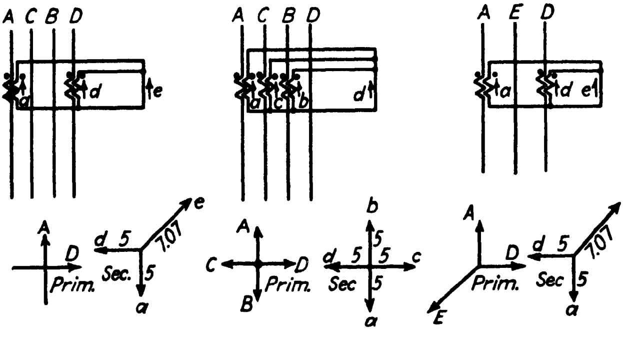


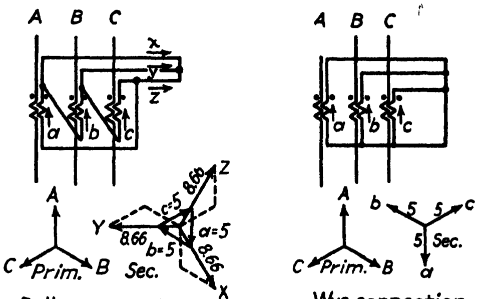
FIG. 180. Typical ratio and phase-angle curves, current transformer.



Two-phase, 4-wire Two-phase, 4-wire interconnected Two-phase, 3-wire

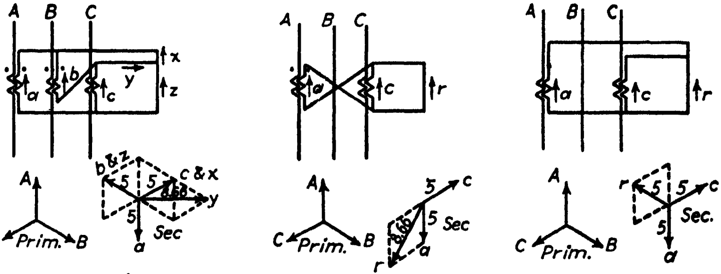
FIG. 181. Current-transformer connections for two-phase.

the high-voltage connections near the normal height of the high-voltage lines. In other cases the current transformer is mounted on the steel structure of the substation, and a small height is



Delta connection

Wye connection



Z connection Reversed V connection

FIG. 182. Current-transformer connections for three-phase.

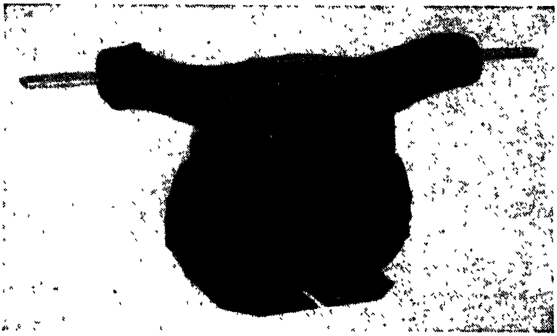


FIG. 183. Dry-type current transformer for 15,000 volts.

desired. In transformers of this kind, therefore, a porcelain casing is used which combines the functions of the transformer tank with those of the porcelain casing of the high-voltage bushing. The high-voltage winding is insulated from the low-voltage winding and core in the usual way, and the whole transformer is mounted inside the porcelain. The high-voltage leads are studs brought out through the porcelain near the top. Figure 185 is an example of this construction.

Through-type Current Transformers. Sometimes accuracy is not the most important consideration in a current transformer. In circuits liable to very heavy short circuits the ability of the transformer to withstand the stresses caused by such currents may be more important than extreme accuracy. In such a case the bar type or the window type of current transformer has an advantage. In these types the primary winding consists of a single conductor passing straight through the opening in the core, as distinguished from a primary winding of several turns. The primary conductor may be supplied as a part of the transformer (bar type), or the transformer may consist of a secondary winding

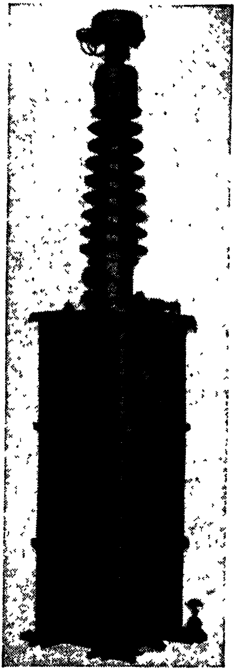


FIG. 184. Oil-insulated current transformer for 115,000-volt circuit.

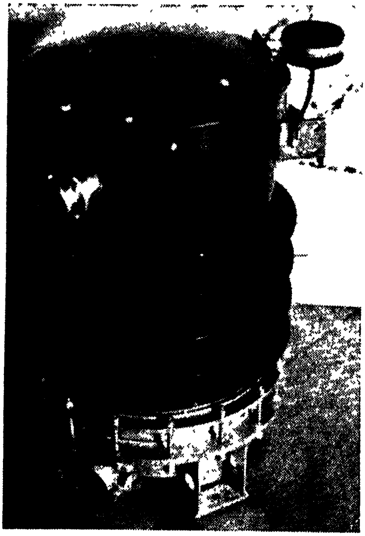


FIG. 185. Oil-insulated current transformer in porcelain case.

on a core having an opening through which a cable or bus bar is to be run (window type). In such transformers the mechanical forces caused by short-circuit currents can be balanced within the transformer itself and therefore are not likely to cause damage.

Since the primary winding of these types is limited to one turn, however, its ampere turns are equal to the current rating of the transformer and cannot be increased. For low ratios this puts these types at a disadvantage with regard to accuracy as compared with the wound primary. Even at fairly low ratios, however, the single-turn primary may give fair accuracy if the burden is small.

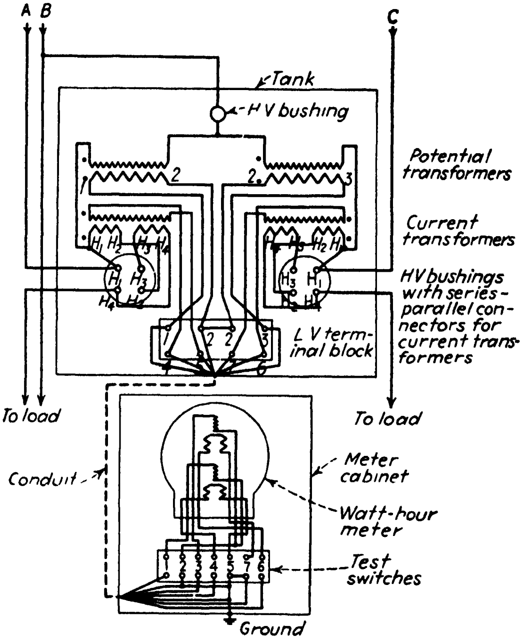


FIG. 186. Three-phase metering outfit.

Metering Outfits. All the instrument transformers needed for a given circuit can be assembled in a tank and permanently connected together. Such an assembly is called a *metering outfit.* It simplifies the connections and is usually somewhat less expensive than the corresponding separate transformers, especially in the higher voltage classes. Figure 186 shows a diagram of connections for a three-phase three-wire metering outfit.

CORRECTION FOR INSTRUMENT-TRANSFORMER ERRORS

Modern instrument transformers are so accurate that it is usually unnecessary to correct for their errors in commercial measurements. In laboratory measurements where the best possible accuracy is desired, corrections are sometimes made. The correction to be applied to a wattmeter reading can be derived as follows:

Let the true voltage and current in a circuit be represented by OE and OI, respectively (Fig. 187), and suppose that the instrument transformers deliver to the meter OE'' and OI'', different in magnitude and in phase from OE and OI as shown. By the standard convention both β and γ are positive when the reversed secondary vector leads the primary vector. The figure, therefore, shows a positive β and a negative γ.

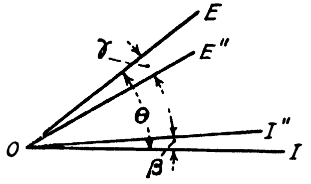


FIG. 187. Effect of instrument transformer errors.

The true power in the circuit is

$$P = EI \cos \theta$$

and the wattmeter reading is

$$W = E''I'' \cos (\theta - \beta + \gamma)$$

therefore

$$P = W \frac{EI \cos \theta}{E''I'' \cos (\theta - \beta + \gamma)}$$

but

$$\frac{E}{E''} = k_v = \text{“per cent ratio”} \div 100$$

for the potential transformer and

$$\frac{I}{I''} = k_c = \text{“per cent ratio”} \div 100$$

for the current transformer. Therefore

$$P = W \times k_v \times k_c \times \frac{\cos \theta}{\cos (\theta - \beta + \gamma)}$$

where $\cos \theta$ = true power factor of the circuit
γ = phase angle of the potential transformer
β = phase angle of the current transformer

Example: The wattmeter on a certain circuit reads 1,500 kilowatts, the voltmeter reads 6,900 volts, and the ammeter reads 276 amperes. A potential transformer is in use rated 200 volt-amperes and having the characteristics shown in Fig. 175. Its total burden is 100 volt-amperes at 85 per cent power factor. The current transformer is rated $^{400}/_{5}$ amperes, and its characteristics are shown in Fig. 180. Its burden is 12.5 volt-amperes at 90 per cent power factor. What are the volts, amperes, and kilowatts, corrected for instrument-transformer errors?

Solution: The burden on the potential transformer is 50 per cent of its rated output. Referring to curve 2 in Fig. 175 we find that the ratio is 100.28 per cent at this burden and the phase angle is 6 minutes, leading (or positive). The corrected voltmeter reading is

$$\text{Volts} = 100.28 \text{ per cent of } 6{,}900 = 6{,}919.3 \text{ volts}$$

The current in the circuit is $^{276}/_{400} = 69$ per cent of the rating of the current transformer. From curve *B* 0.5 (Fig. 180) we find the corresponding ratio to be 99.90 per cent, and the phase angle to be -1 minute. The corrected ammeter reading is therefore

$$\text{Amperes} = 99.90 \text{ per cent of } 276 = 275.72 \text{ amperes}$$

The apparent power factor of the circuit from the meter readings is

$$\frac{1{,}500{,}000}{6{,}900 \times 276} = 0.78765 = \cos(\theta - \beta + \gamma)$$

Therefore

$$\begin{array}{rl} \theta - \beta + \gamma = & 38^\circ \quad 2' \\ +\beta \quad\;\; = & \quad\; -1' \\ -\gamma = & \quad\; -6' \\ \hline \end{array}$$

adding,

$$\theta = 37^\circ \quad 55'$$

and

$$\cos\theta = 0.78890$$

Substituting these figures in the formula, we get the corrected wattmeter reading

$$P = 1{,}500 \times \frac{100.28}{100} \times \frac{99.90}{100} \times \frac{78{,}890}{78{,}765} = 1505.1 \text{ kw}$$

Frequently, as in this case, one error tends to neutralize another, and the total error is small—less than 0.5 per cent in the example. If it is desired to make corrections, the manufacturer of the instrument transformers can usually supply "typical" curves for the kind of potential and current transformers in use, free of charge. These represent the performance of any individual unit very closely. To get the maximum possible accuracy, however, it is necessary to have curves made for the particular unit in use. Such curves require special tests, and a charge is usually made for them.

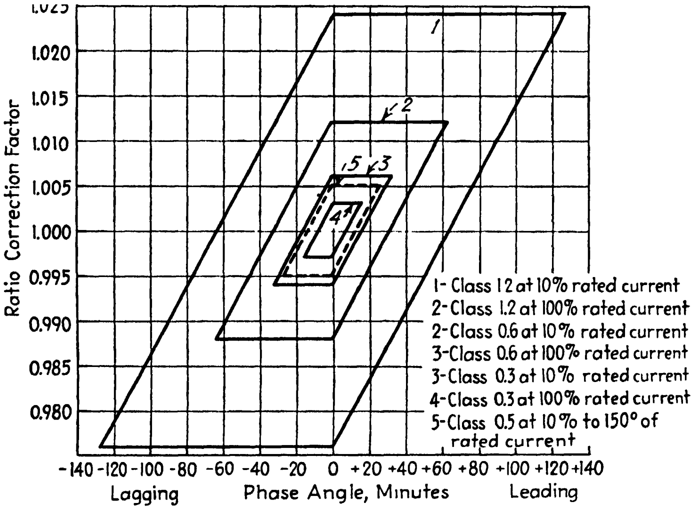


FIG. 188. Relation of ratio-correction factor and phase angle for various accuracy classes of current transformers.

The American Standards include a section on instrument transformers which specifies standard burdens and standard accuracies. The following paragraphs, quoted from the Standards, apply to instrument transformers for metering service. The section also contains standards for transformers used in relay service, but this information is not included here. Those interested should refer to the complete Standards.

Figure 188 shows the relation between ratio correction factor and phase angle required to meet certain accuracy classes. For example, if the ratio correction factor of a certain current transformer with a given burden is 1.004 at 100 per cent of rated current and 1.002 at 10 per cent, and if the corresponding phase angles are +15 and 0 minutes, the accuracy class of the transformer at that burden would be 0.6. Figure 188 combines the information in Figs. 13.031*A*, *B*, *C*, and *D* of the Standards.

Current-transformer Standard Burdens, Standard Accuracy Classes, and Standard Application Data

13.030 Standard Burdens for Current Transformers for Rating Purposes

a. Standard burdens for rating purposes shall have constant resistance and inductance over the entire current range on which they are used.

TABLE 13.030

Standard Burdens For
Standard 5-Ampere Secondary-Current Transformers

Designation of Burden	Standard Burden Characteristics		Standard Secondary-Burden Impedance Ohms and Power Factor and Standard Secondary Volt-Ampere Burdens					
	Resistance Ohms	Inductance Millihenrys	For 60-Cycle and 5-Ampere Secondary Current			For 25-Cycle and 5-Ampere Secondary Current		
			Impedance Ohms	Volt-Amperes*	Power Factor	Impedance Ohms	Volt-Amperes*	Power Factor
B-0.1	0.09	0.116	0.1	2.5	0.9	0.0918	2.3	0.98
B-0.2	0.18	0.232	0.2	5.0	0.9	0.1836	4.6	0.98
B-0.5	0.45	0.580	0.5	12.5	0.9	0.4590	11.5	0.98
B-1	0.5	2.3	1.0	25	0.5	0.617	15.4	0.81
B-2	1.0	4.6	2.0	50	0.5	1.234	30.8	0.81
B-4	2.0	9.2	4.0	100	0.5	2.468	61.6	0.81
B-8	4.0	18.4	8.0	200	0.5	4.936	123.2	0.81

* In accordance with 10.130 the burden may also be designated by means of the volt-ampere characteristic: *e.g.*, 25 volt-ampere at 5 amperes or 50 volt-amperes at 5 amperes.
See 13.030 (*b*).

b. Standard burdens for 5-ampere* secondary, 60- and 25-cycle† standard current transformers shall have resistance and inductance values, together with impedance ohms, volt-amperes, and power factors as shown in Table 13.030.‡

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* For current transformers having a secondary current rating other than the standard 5-ampere rating, the corresponding nonstandard burden should be derived from the standard burdens by the inverse square ratio of the nonstandard current to the standard 5-ampere current. For example, for a 1-ampere secondary-current transformer the burden would be twenty-five times the tabular values of ohms resistance and impedance as given in Table 13.030.

† Burdens for other frequencies shall have the same value of resistance and inductance as those given in Table 13.030.

‡ Burdens *B* 0.1, *B* 0.5, and *B* 2 correspond to the *X*, *Y*, and *Z* burdens previously used.

13.031 Standard Accuracy Classes for Current Transformers for Metering Service

a. The accuracy classification of current transformers for metering service shall be based on the requirement that the transformer correction factor§ (TCF) shall be within specified limits over a specified range of power factor of the load being metered.

b. For purposes of standardization, the limits of transformer correction factor shall be specified at 100 per cent of rated primary current and 10 per cent of rated primary current.

c. For the purposes of accuracy classification, the rated secondary current shall be 5 amperes.

d. The standard accuracy classes and corresponding limits of transformer correction factor (TCF) shall be as shown in Table 13.031.

TABLE 13.031

Standard Accuracy Classes and Corresponding Limits of Transformer Correction Factors for Current Transformers for Metering Service *

Accuracy Class	Limits of Transformer Correction Factor				Limits of Power Factor (Lagging) of Metered Power Load
	100-Percent Rated Current		10-Percent Rated Current		
	Minimum	Maximum	Minimum	Maximum	
1.2	0.988	1.012	0.976	1.024	0.6-1.0
0.6	0.994	1.006	0.988	1.012	0.6-1.0
0.3	0.997	1.003	0.994	1.006	0.6-1.0
0.5	0.995†	1.005†	0.995	1.005	0.6-1.0

* See Figures 13.031 (A) to (D).
† These values also apply to 150-percent rated current.

The relationship between the limits of ratio correction factors and phase angles for the limiting values of transformer correction factors given in Table 13.031 is shown by the parallelograms given in Figures 13.031 *A*, *B*, *C*, and *D*.

e. For any known ratio correction factor (RCF) of a given transformer, the positive and negative limiting values of the phase angle β in minutes may be adequately expressed as follows:

$$\beta = 2600\,(\mathrm{RCF} - \mathrm{TCF})$$

§ For the purpose of this standard the term *transformer correction factor* (TCF) is used instead of the more complete term *instrument-transformer correction factor* defined in 10.134. This term is used to designate the factor by which the watt-hour meter registration or the wattmeter indication must be multiplied to correct for the error introduced by the transformer through the combined effect of the ratio correction factor (RCF) and phase angle (β).

in which TCF is taken as the minimum and maximum transformer correction factor specified in *d* above.

The limiting values of the ratio correction factor are the same as the limits of transformer correction factor given in *d* above, since the phase angle of the current transformer does not introduce a significant error when it is small and when the load power factor is 1.0. These limits of ratio correction factor together with the corresponding limits of phase angle keep the transformer correction factor within the specified limits for all values of power factor (lagging) of the metered power load between 0.60 and 1.00.

f. A current transformer shall be given a standard accuracy rating in accordance with the standard accuracy class (or classes) in which it falls for the specified standard burden (or burdens).

TABLE 13.036
Standard Burdens for Potential Transformers

Designation of Burden	Secondary Volt-Amperes	Burden Power Factor
W	12.5	0.10
X	25	0.70
Y	75	0.85
Z	200	0.85

TABLE 13.037
Standard Accuracy Classes for Potential Transformers for Metering Service *

Accuracy Class	Limits of Transformer Correction Factor	Limits of Power Factor (Lagging) of Metered Power Load
1.2	1.012-0.988	0.6-1.0
0.6	1.006-0.994	0.6-1.0
0.3	1.003-0.997	0.6-1.0

g. In practice, current transformers shall be designated in reference to accuracy rating by the accuracy-class number followed by the burden designation. For example: 0.6 *B* 2.

Potential-transformer Standard Burdens, Standard Accuracy Classes, and Standard Application Data

13.036 Standard Burdens for Potential Transformers for Rating Purposes. Standard burdens for accuracy rating purposes shall have constant resistance and inductance over the entire voltage range on which they are used. Standard burdens are those listed in Table 13.036. The secondary volt-ampere and power-factor values are at rated frequency and at a secondary voltage of 120 volts.

13.037 Standard Accuracy Classes for Potential Transformers for Metering Service

a. The accuracy classification of potential transformers for metering service shall be based on the requirement that the transformer correction factors shall be within specified limits over a specified range of power factor of the load being metered.

b. Standard accuracy burden ratings and volt-ampere thermal output ratings shall be on the basis of 120-volt secondary for all transformers listed in Groups 1, 2, and 3 of Table 13.016, and the same accuracy burden ratings and also the same volt-ampere thermal output ratings shall also apply to the 69.3-volt secondary of those transformers listed in Group 3.

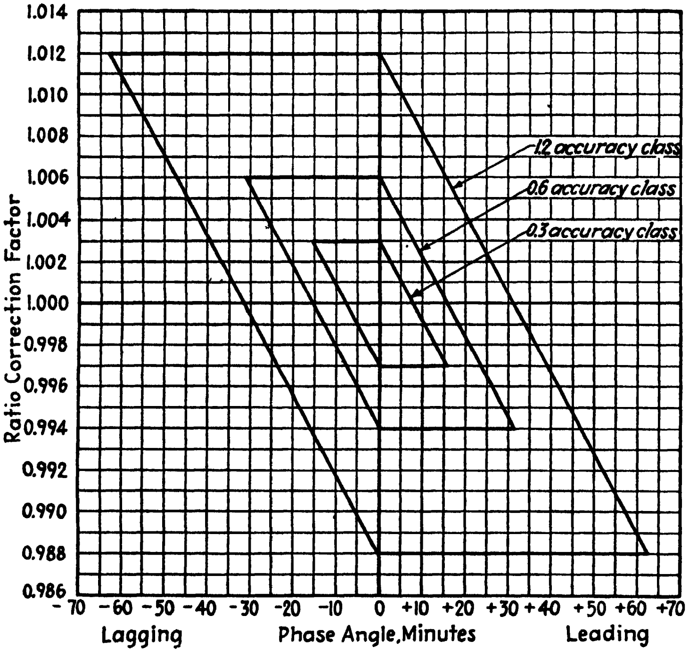

FIG. 189. Relation of ratio-correction factor and phase angle for various accuracy classes of potential transformers.

c. The standard accuracy classes and corresponding limits of transformer correction factor for potential transformers shall be as listed in Table 13.037.

d. For any known ratio correction factor (RCF) of a given transformer, the positive and negative limiting values of the phase angle γ in minutes may be adequately expressed as follows:

$$\gamma = 2600\ (\text{TCF} - \text{RCF})^*$$

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* For the purpose of this standard the term *transformer correction factor* (TCF) is used instead of the more complete term *instrument-transformer*

in which TCF is taken as the maximum and minimum transformer correction factor specified in *c*.

The limiting values of the ratio correction factor are the same as the limits of the transformer correction factor, since the phase angle of the potential transformer does not introduce a significant error when it is small and when the load power factor is 1.0. These limits of ratio correction factor, together with the corresponding limits of phase angle, keep the transformer correction factor within the specified limits for all values of power factor (lagging) of the metered power load between 0.6 and 1.0.

The relationship between the limit of ratio correction factor and phase angle is shown by the parallelograms in Fig. 13.037.

e. These limits shall apply from 10 per cent below to 10 per cent above rated primary voltage at rated frequency and from zero burden on the potential transformers to the specified burden on 120- or 69.3-volt basis.

f. In practice, a potential transformer shall be designated in reference to accuracy rating by the accuracy class number followed by the burden designation, *e.g.*, 0.6 W.

Figure 189 shows graphically the relations which can exist between ratio and phase angle for the several accuracy classes.

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correction factor defined in 10.134. This term is used to designate the factor by which the watthour meter registration or the wattmeter indication must be multiplied to correct for the error introduced by the transformer through the combined effect of the ratio correction factor (RCF) and phase angle (γ).

CHAPTER XX

CURRENT-LIMITING REACTORS

The factor which limits the current delivered to a short circuit on a power system is the impedance of the system, including lines and apparatus in the path of the current. Impedance is defined as

$$Z = \sqrt{R^2 + X^2}$$

where Z = impedance, ohms
R = resistance, ohms
X = reactance, ohms

Of the two elements under the radical, resistance is negligible in most power systems in comparison with reactance, and the short-circuit current is limited practically by the reactance of the circuit.

Reactance. The reactance of a circuit depends on the frequency and on the flux linkages per ampere, *i.e.*, on the inductance of the circuit.

$$X = 2\pi f L$$

where X = reactance, ohms
f = frequency, cycles per second
L = inductance, henrys

If the reactance of a circuit is small, the short-circuit current will be high, and it is necessary to install large specially braced conductors, large circuit breakers, etc., to handle such currents. An increase in the reactance of the circuit may considerably decrease the cost of the apparatus. For example, a certain circuit may require a 1,000,000-kva circuit breaker to handle short-circuit currents. If the reactance is doubled, a 500,000-kva circuit breaker will be adequate, and the cost of the additional reactor may be a small part of the saving in the circuit breaker.

Reactance not only limits the short-circuit current, but it also increases the regulation of the system, especially at low power factors. This, in itself, is not desirable. It is a part of the price paid for short-circuit protection, and it can be compensated for by means of voltage regulators.

Current-limiting Reactors. The simplest way to add reactance to a circuit is by means of a current-limiting reactor, which is a coil of wire or cable with an air core. Figure 190 is an example of an air-cooled reactor. The coil is wound with spacers between the turns to allow free circulation of air, and the turns are braced to resist the mechanical forces to which they are subject. The base and the cap in this design are made of reinforced concrete, and the whole device is supported on insulating feet.

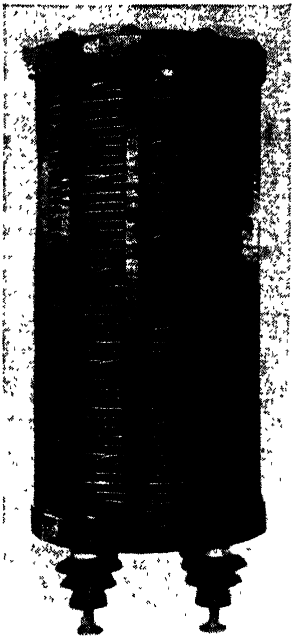


FIG. 190. Air-cooled rent-limiting reactor.

Air Cores. The question naturally arises, why not put iron into the core, as is done in paralleling reactors, and thus increase the magnetic flux? The answer is that current-limiting reactors have a function quite different from that of paralleling reactors. Paralleling reactors are designed to equalize the impedance of transformers connected in parallel under normal load conditions—up to full load or possibly double load—and an iron core with air gaps can be made to operate without saturation in this range. As soon as saturation begins, the magnetic flux begins to increase less rapidly than the current. In other words, the reactance in ohms becomes less and less. This does no harm in paralleling reactors, since it occurs above the range of current where the paralleling reactor is intended to be effective. Current-limiting reactors, however, are required to operate without saturation up to twenty or thirty times full load current, keeping the same ohms reactance. A nonsaturating material is therefore necessary for the core.

Design Features. Since the primary function of a current-limiting reactor is protection at times of short circuit, it must be designed to withstand the heating and the mechanical and electrical stresses which occur at such times.

Heat is generated in the reactor under short-circuit conditions much faster than it is dissipated, and the excess raises the temperature of the copper. Since copper loses tensile strength rapidly above 250°C, the temperature attained at the end of the short circuit must not exceed this figure, and the temperature rise depends on both the magnitude and the duration of the current. For instance, if the normal temperature rise and the normal current of two reactors are the same, and if the short-circuit current in reactor *A* is one-half that of *B*, then reactor *A* can remain on short circuit four times as long as *B*. The permissible duration of a given short-circuit current is determined in the design by the cross section of the conductor. It is generally assumed that all the heat generated during the time of short circuit is stored in the copper. This is not exactly true, but the error is on the conservative side.

The mechanical forces in current-limiting reactors are of two kinds, those within the coil itself and those between adjacent reactors. Within the coil the forces tend to draw the wires closer together and to increase the inside diameter. The spacers between turns and the support of the winding must be strong enough to withstand these forces and must also allow ventilation of the winding. The force between adjacent reactors depends on the proportions of the coils and on their separation. Usually the clearance required for the voltage is sufficient to limit these forces to a point where no bracing is required beyond bolting the feet to the supporting structure.

Electrical stresses may be of fundamental frequency or may be caused by transients. The voltage at fundamental frequency across a coil at the time of short circuit is equal to the reactance drop in the coil. As a limit it may approach the voltage of the circuit between line and neutral. Transients may be set up by oscillations between the reactor and the capacitance of the circuit. Protection from bad effects of transients may be obtained by connecting a suitable arrester in shunt with the reactor.

Application. Current-limiting reactors are protective devices and should be located as near as possible to the apparatus which they are to protect. Several typical uses are described below.

1. *Generator Reactors.* When several large generators are in parallel in one station, it may be desirable to install reactors in the leads between each generator and the bus. This will limit the current which can be delivered by the other generators to a

generator in which a fault may develop. Generator reactors are in the circuit whenever the generator is in use and therefore represent a continuous, though small, energy loss.

2. *Bus Reactors.* In order to avoid the energy loss and the voltage drop caused by generator reactors, the bus can be cut into sections so that each section is connected to one generator and a suitable number of feeders. Various bus sections can then be connected together through reactors. Each generator normally carries its own load, and the bus reactors carry current only when there is an interchange of power among the units.

3. *Tie-line Reactors.* These are connected in the tie lines between two generating stations or substations. Usually one half of the total reactance is connected near each end of the tie line, since the most probable location of a fault is between the two stations.

4. *Feeder Reactors.* These are used to localize the voltage drop caused by trouble on a feeder. They enable smaller feeder circuit breakers to be used and prevent opening the main circuit breaker and thus dropping load unnecessarily in case of a fault on the feeder.

Oil-immersed Reactors. The dry-type reactor can be built for circuits up to 25 kilovolts for outdoor use and up to 34.5 kilovolts for indoor use. For higher voltages and for locations where better protection is required, oil-immersed reactors are used. The reactor is mounted in a tank similar to a transformer tank and supplied with bushings to bring the leads out.

One of the problems in designing an oil-immersed reactor is to prevent the flux from spreading out and returning through the tank wall, causing heating and loss. Various schemes of shielding have been tried. One is to put a short-circuited shield of copper between the reactor and the tank wall. The eddy currents in the copper choke the flux out of the case but cause an appreciable loss. Another scheme is the barrel shield, shown in Fig. 191. A sort of bird cage of laminated iron surrounds the reactor. This provides a low reluctance path for the return flux and keeps it out of the tank wall. Some saturation of the shield occurs with this arrangement, and the ohms reactance decreases slightly between small currents and large currents. A recent scheme, and the best thus far, is shown in Fig. 192. It consists in welding bundles of laminated iron to the inside of the tank wall. With this arrange-

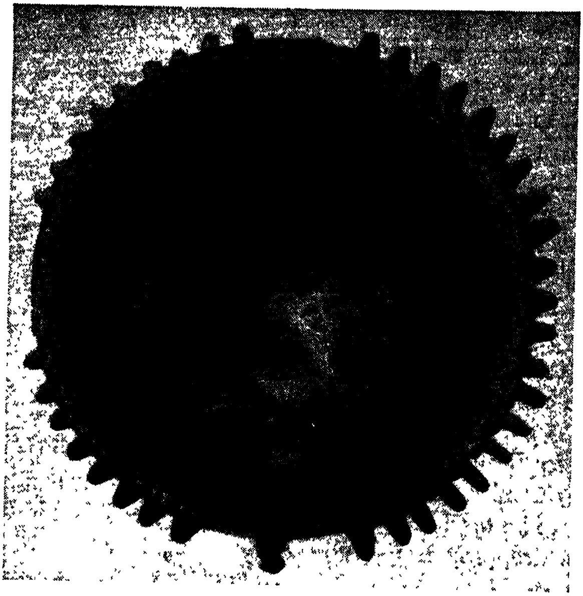


FIG. 191. Barrel shield for current-limiting reactor.

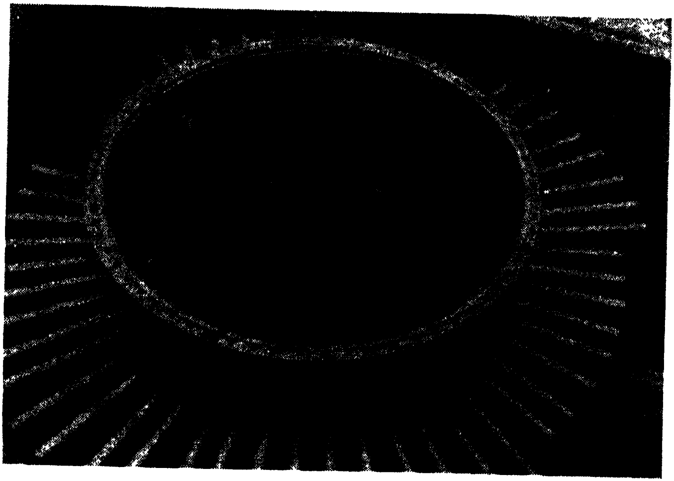


FIG. 192. Shield welded to wall of tank for current-limiting reactor.

ment the loss is kept down, and the ohms reactance practically remains constant.

Advantages and Disadvantages. Some of the advantages of using current-limiting reactors are

1. Protection of circuit breakers, bus structures, etc., from mechanical injury caused by high short-circuit currents.
2. More selective relay operation because of the reduction in feeder short-circuit currents. This enables the defective feeder to be cut off without materially affecting the voltage of the system.
3. Reduction in the heating and in the mechanical forces on apparatus and cables involved in the short circuit.
4. Better parallel operation.

The disadvantages are

1. Slightly poorer regulation and lower power factor.
2. A small energy loss.
3. Cost and space requirements of the reactor.

CHAPTER XXI

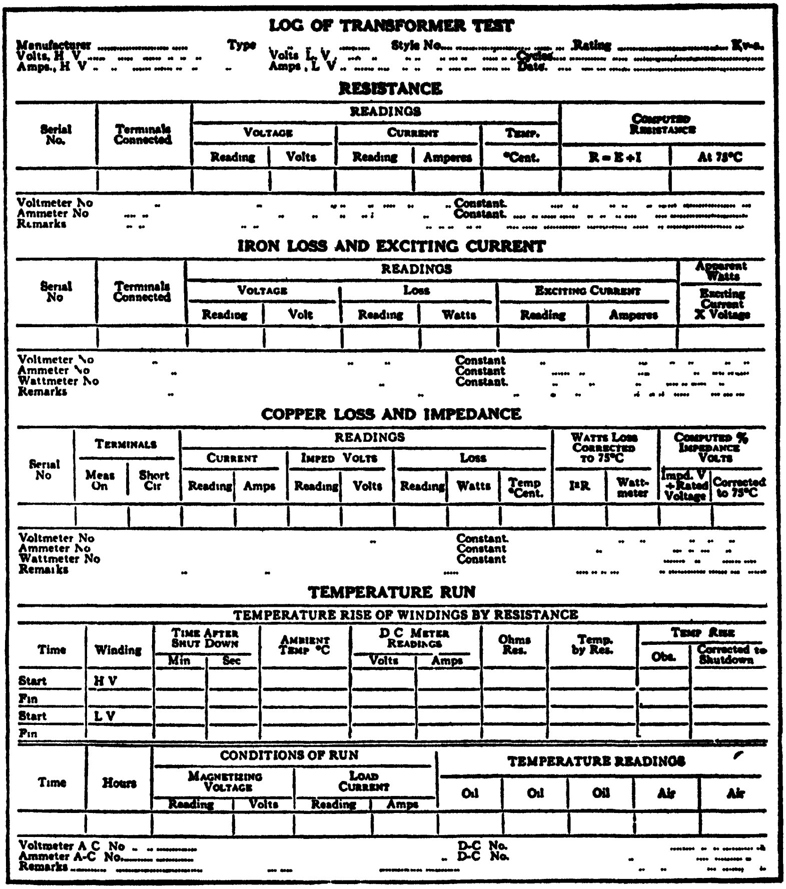
TRANSFORMER TESTING

Transformer testing can be divided into three classes: manufacturers' tests, purchasers' acceptance tests, and purchasers' periodic tests. The manufacturer tests every transformer before it is shipped to prove that the design, manufacture, and material are correct and that the transformer will behave satisfactorily in service. The purchaser tests large and important transformers and those having special guarantees to prove that the guarantees have been met. The tests for this purpose are largely the same ones used by the manufacturer, so the acceptance tests are usually made at the factory. Sometimes the purchaser sends an inspector to witness the tests, and sometimes he merely calls for certified copies of the factory test sheets. The purchasers' periodic tests on transformers in service are those necessary to show that the transformer is suitable for continued service.

Manufacturers' Tests and Purchasers' Acceptance Tests. The manufacturers' tests and the purchasers' acceptance tests include some or all of the following:

1. Resistance measurements.
2. Ratio tests.
3. Polarity tests.
4. Excitation (no-load) loss and exciting current.
5. Impedance (load) loss and impedance voltage.
6. Temperature test.
7. Insulation tests.
    a. Impulse tests (when required).
    b. Applied potential.
    c. Induced potential.
    d. Insulation resistance.

A large and important transformer would be given this complete list of tests by the manufacturer in order to have a record of all its characteristics and to be sure that the design, manufacture, and material are suitable for the service. On the other hand, transformers which are manufactured in quantities would have the complete list of tests applied to only a few units to prove the design. Subsequent units would be given tests 2, 3, 4, 7*b*, and 7*c* to prove that the material and workmanship in each unit were suitable.



LOG OF TRANSFORMER TEST

Manufacturer Type Style No. Rating Kv-a.
Volts, H V Volts L V Cycles
Amps., H V Amps, L V Date

RESISTANCE

Serial No.	Terminals Connected	READINGS					Computed Resistance	
		Voltage		Current		Temp.		
		Reading	Volts	Reading	Amperes	°Cent.	R = E ÷ I	At 75°C

Voltmeter No Constant
Ammeter No Constant
Remarks

IRON LOSS AND EXCITING CURRENT

Serial No	Terminals Connected	READINGS						Apparent Watts
		Voltage		Loss		Exciting Current		Exciting Current X Voltage
		Reading	Volt	Reading	Watts	Reading	Amperes	

Voltmeter No Constant
Ammeter No Constant
Wattmeter No Constant
Remarks

COPPER LOSS AND IMPEDANCE

Serial No	Terminals		READINGS							Watts Loss Corrected to 75°C		Computed % Impedance Volts	
			Current		Imped Volts		Loss						
	Meas On	Short Cir	Reading	Amps	Reading	Volts	Reading	Watts	Temp °Cent.	I^2R	Watt-meter	Impd. V ÷ Rated Voltage	Corrected to 75°C

Voltmeter No Constant
Ammeter No Constant
Wattmeter No Constant
Remarks

TEMPERATURE RUN

TEMPERATURE RISE OF WINDINGS BY RESISTANCE

Time	Winding	Time After Shut Down		Ambient Temp °C	D C Meter Readings		Ohms Res.	Temp. by Res.	Temp Rise	
		Min	Sec		Volts	Amps			Obs.	Corrected to Shutdown
Start	H V									
Fin										
Start	L V									
Fin										

Time	Hours	CONDITIONS OF RUN				TEMPERATURE READINGS				
		Magnetizing Voltage		Load Current		Oil	Oil	Oil	Air	Air
		Reading	Volts	Reading	Amps					

Voltmeter A C No D-C No.
Ammeter A-C No. D-C No.
Remarks

FIG 193. Form for transformer tests.

The details of making these tests and the various acceptable methods are too numerous to be given here. For a complete and authoritative treatise, the reader is referred to the "Test Code for Transformers and other Induction Apparatus," issued by the ASA. The paragraphs below, however, give some generally used methods of making these tests.

General. Accurate test results depend on good meters accurately calibrated and on careful observation and recording of results. Records are facilitated if a form is prepared in advance, and Fig. 193 shows a form which has been found useful. Tests should be made at the rated voltage and frequency of the transformer and with a sine wave of voltage, as nearly as possible. If the wave shape differs from a sine, the iron loss and exciting current must be corrected to a sine-wave basis.

Resistance. Resistance measurements may be made by means of a bridge, or by the drop-of-potential method. The latter method is sometimes more convenient, especially when making tests in the field. Direct current is needed, preferably from a storage battery, and a regulating resistance, a direct-current ammeter, and a direct-current voltmeter are required. Connections are made according to Fig. 194. The current used for resistance measurements should be small—preferably not more than 15 per cent of the rated current of the winding being measured. This is to avoid heating the winding and thereby changing its resistance. For the same reason, the current should be allowed to flow in the winding only long enough to get the readings. Several readings at different currents should be taken, and their average should be taken as the final reading. The resistance is calculated according to Ohm's law,

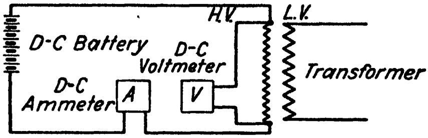


FIG. 194. Connections for resistance measurement.

$$\text{Resistance} = \frac{\text{volts}}{\text{amperes}}$$

It is extremely important to know the temperature at which the resistance is measured, both because the standard method of stating resistance is to reduce it to 75°C and because the temperature of the *cold resistance* gives the starting point for calculating the temperature rise in the heat run.

If the transformer has been in oil for several hours without load and without excitation, its coils may be assumed to be at the same temperature as the top oil. If the transformer is out of oil, however, several thermometers should be placed between coils with their bulbs as closely in contact with the coils as possible and an average of the readings should be taken as the coil temperature.

The measured resistance is corrected to 75°C by the formula

$$\text{Resistance at } 75^\circ = \frac{234.5 + 75}{234.5 + t} \times \text{resistance at } t^\circ$$

Ratio and Polarity. Ratio and polarity are conveniently measured by comparison with a standard transformer of the same ratio and of known polarity, as shown in Fig. 195. The transformer to be tested is excited in parallel with the standard, and the two secondaries are connected in parallel, with a voltmeter in the connection between two terminals, as shown. If the voltmeter reads zero, the two transformers are alike in ratio and polarity. If the polarity is opposite, the voltmeter will read double the secondary voltage of one transformer. And if the two transformers are alike in polarity but different in ratio the voltmeter will indicate the difference.

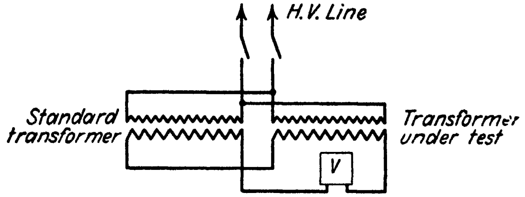


FIG. 195. Connections for ratio and polarity test.

Excitation Loss and Exciting Current. The excitation loss in a transformer is the loss which occurs when the transformer is excited at rated voltage and frequency but without load on the secondary. Besides the core loss, it includes the dielectric loss and the copper loss caused by the exciting current. The two last, however, are usually negligible in comparison with the core loss. Core loss and exciting current are much affected by wave form as well as by voltage and frequency, so steps must be taken to ensure that the voltage wave will be a sine form or else that correction for wave form is made.

A convenient method of making the correction for wave form in core-loss and exciting current measurements is to set the voltage by means of an average voltmeter. The excitation loss is principally a hysteresis loss in the core, and this depends on the maximum flux density, and not on the wave shape. The maximum flux density corresponds to the average of the voltage wave, but the ordinary alternating-current voltmeter indicates the rms value of the voltage, and not the average. The average voltmeter is a direct-current meter of the d'Arsonval type connected in series with a full-wave rectifier. It is usually calibrated to read the same as the rms voltmeter on a pure sine wave. If on a wave of any other form the meter reads, say, 120 volts, it indicates that the actual core loss with the applied voltage and wave form is the same as the loss at 120 volts with a sine wave.

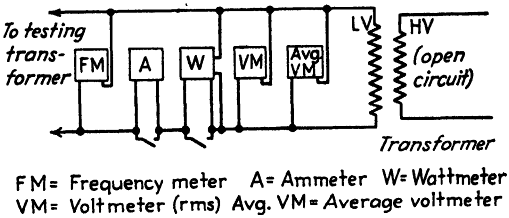

To testing transformer
FM
A
W
VM
Avg VM
LV
HV (open circuit)
Transformer
FM= Frequency meter A= Ammeter W= Wattmeter
VM= Voltmeter (rms) Avg. VM= Average voltmeter

FIG. 196. Connections for excitation-loss and exciting-current test.

Core loss is usually measured on the low-voltage side of the transformer, and the arrangement of instruments is shown in Fig. 196. The switches in parallel with the ammeter and wattmeter are used to shunt these instruments out of the circuit except while they are being read. With connections as shown, adjust the voltage to the rated voltage of the transformer, using the average voltmeter. Read the rms voltmeter. Now disconnect the average voltmeter, and hold the same voltage as before on the rms meter. Read the ammeter and the wattmeter, releasing the button on the voltmeter so that it will be out of circuit while these readings are being taken. Both the ammeter and the wattmeter readings thus taken include the current which flows through the voltage circuit of the wattmeter and are therefore too high. The wattmeter reading is corrected by subtracting E^2 divided by R, where E is the applied rms voltage and R is the resistance of the voltage circuit of the wattmeter. The difference is the excitation loss of the transformer. The current flowing through the voltage circuit of the wattmeter can be found by dividing E by R, but this cannot be subtracted directly from the ammeter reading because it is at a high power factor whereas the exciting current of the transformer is at a low power factor. The ammeter reading can be corrected by disconnecting the wattmeter voltage coil as well as the voltmeter coil from the circuit while the ammeter is being read.

Impedance Loss and Impedance Voltage. The impedance loss, or load loss, of a transformer includes the I^2R loss in the windings and the *stray losses* caused by eddy currents in the windings and by stray fields which cause losses in the case or end frames. Impedance voltage is the voltage needed to circulate rated current through the resistance and reactance of the windings. To measure impedance the low-voltage winding of the transformer is short circuited and instruments are connected as shown in Fig. 197. Adjust the regulating transformer to deliver a low voltage—about 3 to 5 per cent of the rated voltage of the winding in use, for a start—open the ammeter switch, and read the ammeter. Adjust the voltage until the transformer is carrying rated current, and read the voltmeter and wattmeter. The same precautions as above should be taken in reading the instruments and in making corrections. The temperature of the windings should be noted during this test. Then at this temperature.

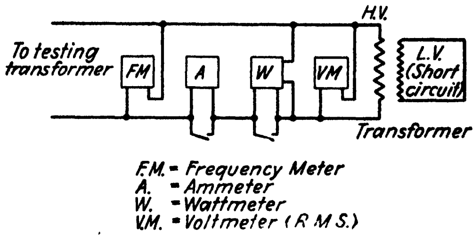


FIG. 197. Connections for impedance test.

Stray loss = impedance watts

− total I^2R, reduced to the same temperature

The stray losses must be separated in order that the total copper loss may be reduced to the standard reference temperature of

75°C. As the temperature rises, the resistance of the winding rises, and consequently the I^2R rises in the same proportion. Stray losses, however, are caused by eddy currents which, in turn, are set up by a voltage induced by the stray flux. This voltage is fixed for a given current in the winding, and therefore the eddy currents are inversely proportional to the resistance. As the temperature rises, the eddy currents decrease. The total load loss, then, at 75°C is the sum of the stray losses and the I^2R loss at this temperature.

$$\text{Stray loss at } 75° = \frac{234.5 + t}{234.5 + 75} \times \text{stray loss at } t°$$

where t is the temperature at which the measurement was taken and

$$I^2R \text{ at } 75° = \frac{234.5 + 75}{234.5 + t} \times I^2R \text{ at } t°$$

The impedance voltage is also separated into its two components in order to calculate the regulation of the transformer. It consists of the resistance drop, which varies with the temperature, and the reactance drop, at right angles to the resistance drop and independent of the temperature.

$$\text{Effective resistance volts} = \frac{\text{impedance watts}}{\text{amperes in the excited winding}}$$

$$\text{Effective reactance volts} = \sqrt{(\text{imped. volts})^2 - (\text{eff. resis. volts})^2}$$

These quantities may be expressed in percentage as follows:

$$\text{\% effective resis. drop} = 100 \times \frac{\text{measured impedance watts}}{\text{rated volt-ampere output}}$$

$$\text{\% impedance volts} = 100 \times \frac{\text{measured impedance voltage}}{\text{rated voltage of exciting winding}}$$

$$\text{\% reactance volts} = \sqrt{(\text{\% imped. volts})^2 - (\text{\% eff. resis. volts})^2}$$

Temperature Test. The temperature test is for the purpose of determining the temperature rise of the transformer under rated load. Before beginning the test a very careful cold-resistance measurement should be made, giving particular attention to determining the temperature of the windings at which the resistance is measured. Complete preparations should also be made to disconnect the power leads quickly at the end of the test and connect the circuit for the hot-resistance measurement so as to get the hot resistance before the windings have time to cool.

The load for the temperature run may be a lamp bank or a resistance load. This requires an extravagant amount of energy, however, and is seldom used. Instead, an opposition method, or *loading-back* method, is sometimes used where two duplicate transformers are available. Connections are shown in Fig. 198. The two transformers are connected in parallel on both the high-voltage and the low-voltage sides. Full rated voltage is applied to the low-voltage side, and a voltage from an external source is inserted in the high-voltage parallel just large enough to circulate

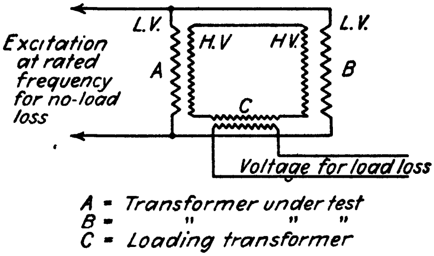

Excitation at rated frequency for no-load loss
L.V.
H.V
H.V
L.V.
A
B
C
Voltage for load loss
A = Transformer under test
B = " " "
C = Loading transformer

FIG. 198. Connections for temperature test.

rated current through the impedance of the two transformers. The transformers are thus normally excited and are carrying their normal current, so the heating conditions correspond to normal load.

The room temperature, or ambient temperature, is determined by several thermometers placed 3 to 6 feet from the transformer and about midway of the height of the transformer and shielded from drafts and abnormal heating. A recommended practice is to put the bulb of the thermometer into a heavy metal cup filled with oil. This gives a good average of the room temperature and does not respond to temporary variations. Another scheme, especially in the case of large transformers, is to use an idle unit similar to the units under test to determine the ambient temperature. Thermometers near the surface of the oil in the idle unit give the reading to be used. The temperature of the oil in the transformer under test is measured by a thermocouple or by an alcohol thermometer with its bulb about 2 inches under the oil in the center of the tank.

With the transformers connected as in Fig. 198, adjust the loading transformer to deliver 2 or 3 per cent of the voltage of the winding to which it is connected, and note the current. If it is in proportion to the voltage, adjust the voltage until rated current flows through the transformers. Now apply a low voltage from the exciting transformer, and increase it gradually until rated voltage is reached. Readjust both circuits occasionally to keep both current and voltage normal as the transformers warm up.

Readings of the oil temperature and of the ambient temperature should be taken at regular intervals until the oil rise becomes constant. This is assumed to be the case when the oil temperature does not vary more than 2°C, and the air temperature not more than 2.5°C in the same direction in 3 hours.

When the temperature has become constant, disconnect the power and measure the hot resistance according to the plan previously made, and immediately put the transformers back on temperature run. Thus little or no time will be lost if it is necessary to make check measurements. The final temperature of the windings is calculated from the expression

$$t_f = \frac{r_f}{r_i} \times (234.5 + t_i) - 234.5$$

where t_i = initial temperature
t_f = final temperature
r_i = initial resistance (cold resistance)
r_f = final resistance (hot resistance)

The temperature rise of the windings is found by subtracting the final ambient temperature from the final temperature t_f, found above, and the oil rise is found by subtracting the final ambient temperature from the final oil temperature.

Since a transformer begins to cool the instant that the power is shut off, it is necessary to correct the measured temperature rise for the time elapsed between shutdown and the instant of measurement. The Test Code prescribes corrections for various classes of transformers. For oil-insulated transformers in which the copper loss does not exceed 7 watts per pound, an arbitrary correction of 1°C per minute is specified, provided that the total elapsed time does not exceed 4 minutes.

One of the two duplicate transformers will probably show a slightly higher rise than the other. This is because one transformer carries the vector sum of the exciting current and the load current while the other carries the vector difference. The higher of the two should be taken as the true reading.

"Compromise" Heat Run. Another method of loading for temperature tests which is used when a single large transformer is to be tested is as follows:

1. Short-circuit one winding of the transformer to be tested.
2. Circulate through the other winding a current sufficient to cause a loss equal to the sum of the normal excitation loss plus the normal impedance loss.
3. Run at this current until the oil-temperature rise above ambient becomes constant. Note the oil-temperature rise.
4. Now reduce the current to normal value, and continue the run until the temperature rise of the winding above the top oil temperature (the *gradient*) becomes constant.
5. The copper rise under full load will be the sum of the top oil-temperature rise above ambient plus the gradient.

This method requires the same care in measuring hot and cold resistance as mentioned in the loading-back method.

INSULATION TESTS

Before shipment from the factory every transformer built by a reputable manufacturer is tested to prove that the insulation is in satisfactory condition as regards cleanness and dryness and that it is adequate to ensure satisfactory operation of the transformer in service. The dielectric test and the induced voltage test are used generally, and sometimes, in addition, the insulation resistance and the impulse tests.

Impulse Tests. Impulse tests are made to prove that the transformer will stand impulses, such as switching surges and, more especially, lightning surges. Such tests are made when called for in the contract and also on some transformers of new design to demonstrate the design. Rather elaborate equipment is needed, and impulse tests are rarely made after the transformer leaves the factory. The test consists in applying to the specified windings of the transformer high-voltage impulses of very steep front, similar to lightning impulses. The impulse test is discussed more in detail in the chapter on Transformer Insulation.

Applied-potential Test. The applied-potential test consists in the application of a high alternating-current voltage between the winding under test and the other windings and ground. The table on page 90 shows the voltage to be applied to standard transformers of various voltage classes, according to the American Standards. The object of this test is to show that the kind and quantity of insulating material in the transformer are adequate and that it is properly placed. Such a test, however, imposes a stress on the insulation, and a frequent repetition might eventually hasten or even cause a breakdown. For this reason the American Standards recommend that the factory insulation test shall not be repeated. An insulation test on new transformers after they are installed should not exceed 75 per cent of the factory test, and the same limit should be placed on transformers rebuilt in the field.

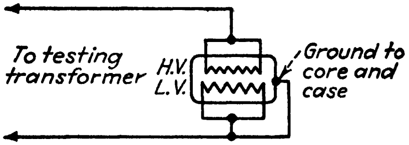


FIG. 199. Connections for applied-potential test.

Periodic insulation tests on transformers in service are usually unnecessary, but if such tests are made, the voltage should be limited to 65 per cent of the factory-test voltage.

In making the test between a winding and ground, all the terminals of the winding under test should be connected together and to one terminal of the testing transformer. All terminals of other windings should be connected together and to the core and tank and to the other terminal of the testing transformer by good metallic connections. The connection is shown in Fig. 199. The voltage of the testing transformer is determined by a voltmeter on the low-voltage side, checked by a sphere gap on the high-voltage side. The test should be started at about a quarter of the required voltage, and the voltage should be raised to full value in about 15 to 30 seconds. It should be held at the test voltage for the required time—usually 1 minute and then reduced to a low value before the circuit is opened.

Induced-potential Tests. The induced-potential test is applied to test the insulation between turns, layers, and sections of the winding, and in windings designed for operation with one end solidly grounded the induced-voltage test is the only low-frequency dielectric test which can be made. This test is made by applying, to one winding, a voltage which is the specified number of times its rated voltage. For power transformers double the rated voltage is generally used, and in order to limit the exciting current, a higher frequency than the rated frequency of the transformer is used. For frequencies up to 120 cycles per second the time of test is usually 1 minute, and for frequencies above 120 cycles the time is reduced in inverse ratio to the frequency.

The test should be started at a quarter of the specified test voltage or less, and the voltage should be increased gradually to the full test voltage in not more than 15 seconds. After being held for the specified time the voltage should be reduced gradually before the circuit is opened.

Insulation Resistance. The insulation resistance of a transformer depends largely on the temperature and on the cleanness and dryness of the windings. Insulation resistance alone, therefore, does not tell much about the strength of the transformer. It does give an indication, however, as to whether the insulation is in proper condition for the application of the dielectric test. In transformers the insulation resistance is expected to be at least 1 megohm per thousand volts of dielectric-test voltage. If it falls below this figure, it points to the presence of dirt or moisture.

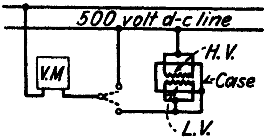


FIG. 200. Connections for measuring insulation resistance.

The most convenient way to measure insulation resistance is by means of a *megger*. This consists of a magneto mounted in a case with a meter and two binding posts for connection to the apparatus to be measured. The meter is calibrated to read directly the megohms in the circuit connected to the terminals.

An alternative method is to use a direct-current voltmeter of high resistance and a direct-current voltage, usually 500 volts. Connection is made as shown in Fig. 200, and two readings are taken, one with the voltmeter directly across the line and the other with the unknown resistance in series with the voltmeter. The insulation of the double-throw switch must be sufficient so that the voltmeter indicates zero when the switch is open. The first reading is proportional to the current flowing through the resistance of the voltmeter itself, which is a known quantity, and the second reading is proportional to the current flowing through the resistance of the voltmeter plus the unknown resistance. Then,

$$R' = R\frac{D - D'}{D'}$$

where R = resistance of the voltmeter
R' = unknown resistance
D = reading with voltmeter only across the line
D' = reading with voltmeter and unknown resistance in series across the line

EFFICIENCY AND REGULATION

In addition to the quantities which are actually measured in transformer testing, it is usually desired to know the efficiency and regulation of the transformer. These quantities are always found by calculation from measured quantities, because actual measurements are difficult to make and are less accurate than the calculated results. Working out the efficiency and regulation is usually regarded as a part of the transformer test.

Efficiency. Efficiency is the ratio of the output to the sum of the output plus the losses.

Unity power factor and rated voltage and frequency are assumed unless otherwise specified, and the load loss is taken at 75°C. The iron loss in watts is constant for all loads on the transformer, being dependent on the voltage and frequency only, but the copper loss varies as the square of the load.

Take, for example, a 300-kva transformer having iron loss of 1.4 kilowatts and full-load copper loss of 2.5 kilowatts. The efficiency may be calculated as follows:

Load	Output, kw.	Core loss, kw.	Load loss, kw.	Total loss, kw.	Input, kw.	Efficiency, %
Full	300	1.4	2.5	3.9	303.9	98.72
¾	225	1.4	1.406	2.806	227.8	98.77
½	150	1.4	0.625	2.025	152.03	98.67
¼	75	1.4	0.156	1.556	76.556	97.97

Several short-cut methods of calculating efficiency are in use, but unless one has many such calculations to make, it is easier to work out the efficiencies than to remember the short cut.

Regulation. The regulation of a constant-potential transformer is the change in secondary voltage, expressed in percentage of rated secondary voltage, which occurs when rated kilovolt-ampere output at a specified power factor is reduced to zero, with constant impressed primary voltage.

Regulation is calculated from the measured resistance and impedance of the transformer, referred to a temperature of 75°C. The formula is

$$\text{Percentage regulation} = mR + nX + \frac{(mX - nR)^2}{200}$$

where m = power factor of the load, expressed as a decimal
n = reactive factor of the load, expressed as a decimal
R = percentage effective resistance drop at 75°C
X = percentage reactance = $\sqrt{Z^2 - R^2}$
Z = percentage impedance at 75°C

Below are given, for convenience, a few corresponding values of power factor and reactive factor.

Power factor	Reactive factor	Power factor	Reactive factor
1.00	0 00	0.75	0.661
0.95	0.312	0.70	0.714
0.90	0.436	0.60	0.800
0.85	0.527	0.50	0.866
0.80	0.600		

The relation between the two quantities is

$$\text{Reactive factor} = \sqrt{1 - (\text{power factor})^2}$$

If the power factor is 100 per cent (or 1.00), m becomes 1.00 and n becomes zero and the regulation formula reduces to

$$\text{Percentage regulation} = R + \frac{X^2}{200}$$

As an example, the 300-kva transformer mentioned above has an effective resistance of

$$R = \frac{2.5}{300} \times 100 = 0.833 \text{ per cent}$$

If the impedance is 3 per cent, the reactance is

$$X = \sqrt{3 \text{ per cent}^2 - 0.833 \text{ per cent}^2} = 2.88 \text{ per cent}$$

and the regulation at 80 per cent power factor will be

$$\text{Regulation} = 0.80 \times 0.833 + 0.60 \times 2.88 + \frac{(0.80 \times 2.88 - 0.60 \times 0.833)^2}{200}$$

$$= 2.41 \text{ per cent}$$

The regulation, if the load is at 100 per cent power factor, will be

$$\text{Regulation} = 0.833 + \frac{2.88^2}{200} = 0.874 \text{ per cent}$$

PURCHASERS' PERIODIC TESTS

These should include a test of the oil and a general inspection of the transformer, as described in another chapter. Some operators favor an insulation test at intervals, but this is not usually regarded as necessary, and if it is applied it should not exceed 65 per cent of the original test voltage (see paragraph on Dielectric Test, page 200). Tests of insulation resistance have little utility except in connection with drying out a new transformer or one which has been damaged by moisture. This leaves the oil test as the only periodic test which is recommended for transformers in service.

CHAPTER XXII

CARE AND OPERATION OF TRANSFORMERS

The National Electrical Manufacturers' Association has published a pamphlet giving instructions for the care and operation of transformers.* These instructions were prepared by the Transformer Committee of the Association, which consists of representatives of most of the transformer manufacturers of the United States. The instructions cover the location, storage, and handling of transformers; inspection preliminary to installation; drying the core and coils; sampling and testing the oil; and drying the oil and filling the transformer. The following paragraphs on care and operation are quoted from this pamphlet.

CARE OF POWER TRANSFORMERS

The idea that a transformer in service needs no attention may lead to serious results. Careful inspection is essential, and the directions given in this section should be followed.

In spite of all precautions, moisture may be absorbed by the transformer if it is of the open type and during the first few days of operation it is well to inspect the inside of the manhole cover for moisture. If sufficient moisture has condensed to drip from the cover, the transformer should be taken out of service and dried. The oil should be tested and dried if necessary.

Closed-type transformers should have their oil tested at top and bottom after the first few days of operation to make sure that no moisture is being given off from the transformer into the oil.

Oil. Samples of oil from all transformers should be drawn and tested at least once every 6 months.

During the first month of service of transformers having a potential of 40,000 volts or over, samples of oil should be drawn each week from the bottom of the tank and tested.

If at any time the oil should test below 17,500 volts, it should be filtered.

Inspection. Closed-type transformers when properly dried and installed will need thorough inspection only infrequently, *i.e.*, only when there are specific indications of trouble. Other types of transformers should be taken out of service periodically for a thorough inspection. The inside of the cover and the tank above the oil should be regularly inspected to see that they are clean, dry, and free from moisture and that the thermometer bulb is clean. If an appreciable amount of dirt or sediment is found inside the case, it is best to take out the transformer and remove the oil from the tank. The transformer and tank should then be cleaned thoroughly, and the oil filtered and tested. In cleaning, only dry cloths or waste should be used. Care should be taken to see that all nuts are tight and all parts in their proper places. If the transformer is water cooled, the cooling coils should be cleaned thoroughly. The transformer and the oil should be replaced in the tank, and when the cover is put on, all cracks and openings tightly closed.

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* NEMA Instructions for the Care and Operation of Transformers," published by the National Electrical Manufacturers' Association, 420 Lexington Ave., New York, N.Y. Price 25 cents.

In the case of water-cooled transformers, the rate of flow should be checked from time to time, and if it is found to have diminished, the cause should be looked for and remedied. The most frequent cause of clogging of cooling coils is the presence of air in the water, resulting in the formation of a scaly oxide.

Removal of Scale from Cooling Coils. Scale and sediment can be removed from a cooling coil without removing the coil from the tank. Both inlet and outlet pipes should be disconnected from the water system and temporarily piped to a point a number of feet away from the transformer, where the coil can be filled and emptied safely. Especial care must be taken to prevent any acid, dirt, or water from getting into the transformer.

All the water should be blown or siphoned from the cooling coils, which should then be filled with a solution of hydrochloric (muriatic) acid, specific gravity 1.10. (Equal parts of commercially pure concentrated hydrochloric acid and water will give this specific gravity.)

It may be found necessary to force this solution into the cooling coils. When this is done, one end of the coil should be partially restricted, so that the solution will not be wasted when the coil is full. After the solution has stood in the coil about an hour, the coil should be flushed out thoroughly with clean water. If all the scale is not removed the first time, the operation should be repeated until the coil is clean, using new solution each time. The number of times it is necessary to repeat the process will depend on the condition of the coil, although ordinarily one or two fillings will be sufficient.

As the chemical action which takes place may be very violent and may often force acid, sediment, etc., from both ends of the coil, it is well to leave both ends partially open to prevent abnormal pressure.

Idle Cooling Coils. When a water-cooled transformer is idle and exposed to freezing temperatures the water must be blown out of the cooling coil. In addition to blowing out the water the cooling coils should be dried by forcing heated air through them. If not convenient to do this the coil should be filled with transformer oil.

OPERATION OF POWER TRANSFORMERS

An artificially cooled transformer should not be run continuously, even at no load, without the cooling medium. Therefore it is essential to maintain a proper circulation in the cooling system.

If the water circulation in a water-cooled transformer is stopped for any reason, the load should be immediately reduced as much as possible and a close watch kept of the temperature of the transformer. When the oil at the top of the tank reaches 80°C, the transformer must be cut out of service at once. This temperature should be recognized as an absolute limit and must not be exceeded. It should be held only during an emergency period of short duration.

Nearly all cooling water will in time cause scale or sediment to form in the cooling coil. The time required to clog up the cooling coils depends on the nature and amount of the foreign matter in the water. The clogging materially decreases the efficiency of the coil and is indicated by a high oil temperature and a decreased flow of water, load condition and water pressure remaining the same.

Temperature. Thermometers should be read daily or more often. If, at rated load or less, the oil temperature reaches 80°C for an oil-immersed self-cooled transformer or an oil-immersed forced-air-cooled transformer or 65°C for an oil-immersed water-cooled transformer, it is advisable to check operating conditions.

Oil-immersed self-cooled transformers or oil-immersed forced-air-cooled transformers should not be operated for long periods of time at oil temperatures in excess of 80°C on account of increased rate of deterioration of the insulation. The oil temperature in these transformers should not be allowed to exceed 90°C even for short periods of time.

If the oil temperature in oil-immersed water-cooled transformers should exceed 65°C at rated load or less, the cooling coils need cleaning, an insufficient amount of cooling water is being used, or the temperature of the cooling water is higher than 25°C. The oil temperature in oil-immersed water-cooled transformers should not be allowed to exceed 75°C even for short periods of time. A lower oil temperature is recommended for oil-immersed water-cooled transformers on account of the greater difference between the temperatures of the windings and of the oil than in oil-immersed self-cooled transformers.

Regardless of oil temperatures as indicated by thermometers, transformers should not be operated continuously at overloads in excess of 1 per cent for each degree that the ambient is below 30°C for air and 25°C for water. In no case should the overload exceed 30 per cent for self-cooled transformers and 25 per cent for water-cooled transformers unless stipulated by the specification or contract. During overloads the transformer should be watched with special care.

Moisture may get into an open-type transformer owing to the fact that as oil is heated and cooled it expands and contracts and therefore the air is expelled from and enters the transformer. If the air which enters the transformer is at the same time cooled off by contact with the cover to below its dew point, moisture will condense.

It is therefore good practice to operate transformers at several degrees above air temperatures at all times. This will largely prevent condensation.

CARE OF DISTRIBUTION TRANSFORMERS IN SERVICE

The following practice is recommended for the care of pole-mounted distribution transformers in service:

1. The oil level should be inspected once every year, and enough oil added to bring the level up to the mark inside the tank or on the oil gage.
2. Periodically the condition of the oil should be inspected, and if necessary the oil should be removed and replaced with good clean oil.
3. A periodic check of the load should be made to make sure a transformer is not being overloaded.

The ASA in 1937 issued "Guides for Operation of Transformers." These guides were revised in 1948, and the paragraphs below give recommendations for loading under special conditions with normal life expectancy. The guides also contain suggested loadings for moderate sacrifice of life expectancy.

American Standard Guide for Loading Oil-immersed Distribution and Power Transformers

C57.32—1948

32.010 Scope. This guide covers general recommendations for loading all types of oil-immersed transformers with Class A insulation, except water-cooled transformers built before 1929. They include transformers immersed in synthetic or nonflammable liquids.

The manufacturer should be asked for recommendations relating to water-cooled transformers built before 1929 and for more specific recommendations for large and important transformers if required.

32.011 Caution. It must be recognized that loads above rating should not be applied without a thorough study of the various limitations involved. Among these limitations are oil expansion, pressure in sealed-type units, bushings, leads, soldered connections, tap changers, and the thermal capability of associated equipment such as cables, reactors, circuit breakers, disconnecting switches, and current transformers. These may constitute the practical limit in load-carrying ability.

Before loading apparatus above rating to the full extent covered in these guides, it is recommended that load capabilities be checked with the manufacturer.

32.012 General. Recommendations in this guide are based on life expectancy of transformer insulation as affected by operating temperature and time.

Transformer life expectancy at various operating temperatures is not accurately known, but the information given regarding loss of life of insulation is considered to be conservative and the best that can be produced from present knowledge of the subject. The effects of temperature on insulation life are being investigated continuously by the transformer subcommittee, and new findings may affect future revision of the guides. The word *conservative* is used in the sense that the expected loss of insulation life for a single recommended overload will not be greater than the amount stated.

The rated kilovolt-ampere output of a transformer is that load which it can deliver continuously at rated secondary voltage without exceeding a given temperature rise measured under prescribed test conditions. The temperature rise on which the rating is based takes into consideration the experience of the industry regarding

a. Insulation life as affected by operating temperature.

b. The ambient temperatures assumed to exist throughout the life of the transformer.

The actual output which a transformer can deliver at any time in service without undue deterioration of the insulation may be more or less than the rated output, depending upon the ambient temperature and other attendant operating conditions.

Practically all of the data in reference to the aging of insulation at different temperatures has been obtained in laboratory tests in which the decrease in mechanical strength has been measured. The relation between the life expectancy of insulation as indicated by laboratory tests and the actual life of a transformer is largely theoretical, so that loading based on such information must be tempered by sound judgment based on experience.

As the evaluation of the cumulative effects of temperature and time in causing deterioration of transformer insulation is not thoroughly established, it is not possible to predict with any great degree of accuracy the length of life of a transformer even under constant or closely controlled conditions, much less under widely varying service conditions.

The change in rate of deterioration with change in temperature has received much study, but the actual values for different operating temperatures are not completely agreed on. An average value which has been used for a number of years is that the rate of deterioration doubles with each 8°C that the temperature of the insulation increases. This value is not accurate for all temperatures or for all points in the life of a transformer. It is given here to show the importance of controlling ambient temperatures in indoor installations by means of ventilation, thus controlling the insulation temperature and life.

Owing to the many variables mentioned and particularly to the many varying conditions of load and ambient to which a transformer can be subjected in service, it is not possible to give definite rules for the loading of transformers. It is only possible to give suggested loadings under specified conditions and look to the user to make the best use of this information for his particular problem.

32.013 Ambient Temperatures and Loading for Normal Life Expectancy. The basic loading condition of a transformer for normal life expectancy is continuous loading at rated kilovolt-amperes and rated delivered voltage with the temperature of the cooling air at no time exceeding 40°C and with the average temperature of the cooling air during any 24-hour period equal to 30°C. For water-cooled transformers comparable temperatures are 30 and 25°C, the 5°C lower average temperature of the cooling medium being to allow for possible less efficient cooling due to coils that are not clean. (It is assumed that operation under the foregoing conditions is equivalent to operation at a continuous ambient temperature of 30°C for cooling air and 25°C for cooling water.)

The hottest spot copper temperature is the sum of the temperature of the cooling medium, the average temperature rise of the copper and hottest spot allowance. For oil-immersed transformers operating continuously under the foregoing conditions with normal life expectancy this temperature has been assumed to be 95°C.

Other usual service conditions, as given in 11.005, must be complied with.*

Years of experience have indicated that a transformer rated in accordance with the standard and operated under the foregoing conditions will have a reasonably long life.

32.015 Loading under Specified Conditions with Normal Life Expectancy.

a. Loading Determined by Measured Temperature. Transformers may be loaded above rating for any period of time provided the hottest spot temperature is not greater than 95°C. Hottest spot temperature indicators are available by which this temperature may be measured. On account of large variations in the difference between the hottest-spot copper and the top-oil temperatures of various designs under full load, oil temperature alone should not be used as a guide in loading transformers.

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* This specifies operation at altitudes not exceeding 3,300 feet (1,000 meters).

However, by taking the temperature rise of the hottest spot copper over top oil (hottest spot copper gradient) into account, oil temperatures may be used as an approximate guide in loading. When so operated for any period of time, the measured top-oil temperature should not exceed the values given in Fig. 32.015*a* for the load being carried. These loads can be applied to any transformer covered by these guides, as they are conservative.

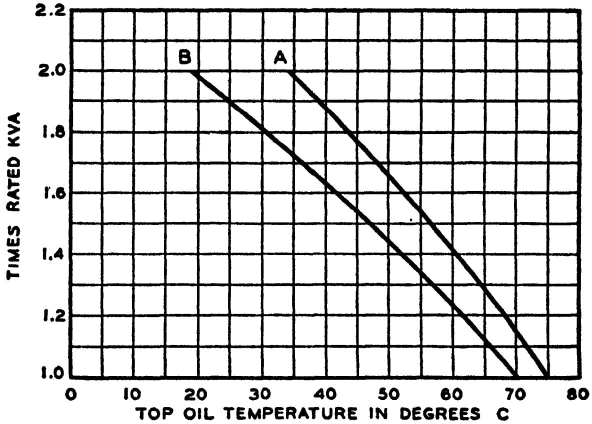


Fig. 32.015a. Loading for normal life expectancy based on top-oil temperature. *A*, Water-cooled, self-cooled, and forced-air-cooled transformers rated 133 per cent or less of self-cooled rating. *B*, Forced-air-cooled transformers rated over 133 per cent of self-cooled rating.

Oil temperatures may be used as a more accurate guide, by using the hottest spot copper gradient of any particular transformer for the load it is carrying at the time. If the hottest spot copper gradient at full load is known, the gradient at other loads may be determined easily by using Fig. 3 in Appendix II. The limiting oil temperature for normal life expectancy for any load, regardless of the time carried, can be determined by subtracting the hottest-spot copper gradient for that load from 95°C.

b. Loading on Basis of Test Temperature Rise. For each degree centigrade in excess of 2° that the test temperature rise is below the standard temperature rise specified in the standard, the transformer load may be increased above rated kilovolt-amperes by the percentages shown in Column 2 of Table 32.015(*c*). Making use of this factor gives the kilovolt-amperes that the transformer can deliver with 55°C temperature rise. The leeway of 2° is to provide for a negative tolerance in the measurement of temperature rise.

Some transformers are designed to have the difference between hottest spot and average copper temperatures greater than the nominal allowance of 10°C. This will result in a temperature rise for average copper of less than 55°C, but the hottest spot copper temperature rise may be at the limiting value of 65°C.

Such transformers should not be loaded above rating as outlined under this heading. The manufacturer should be consulted to give information as to design hottest spot allowances.

c. Loading on Basis of Ambient Temperature. For each degree centigrade that the average temperature of the cooling medium is above or below 30°C for air or 25°C for water, a transformer may be loaded for any period of time below or above its kilovolt-ampere rating as specified in Table 32.015(*c*). Average temperature should be for periods of time not exceeding 24 hours with maximum temperatures not more than 10°C greater than average temperatures for air and 5°C for water. On the basis used in this guide for calculating loss of life, life expectancy will be approximately the same as if it had been operated at rated kilovolt-amperes and standard ambient temperatures over that period.

TABLE 32.015(c)
Loading on Basis of Ambient Temperature

	Percent of Rated Kva	
Type of Cooling	Decrease Load for Higher Temp	Increase Load for Lower Temp
Self-Cooled	1.5	1.0
Water-Cooled	1.5	1.0
Forced-Air-Cooled	1.0	0.75
Forced-Oil-Cooled	1.0	0.75

The use of transformers in cooling air above 50°C or below 0°C or with cooling water above 35°C is not covered by Table 32.015(*c*) and should be taken up with the manufacturer.

d. Loading on Basis of Load Factor. When the load factor for a period of time not exceeding 24 hours is below 100 per cent, the maximum loading of a transformer during that period may be increased above rated kilovolt-amperes by the percentages shown in Table 32.015(*d*) for each per cent that the load factor is below 100 per cent. On the basis used in this guide for calculating loss of life, life expectancy will be approximately the same as if it had been operated at rated kilovolt-amperes during that period.

e. Loading on Basis of Short-Time Loads Above Rating. When short-time loads above rating occur not more than once in any 24-hour period, the maximum loading of a transformer during that period may be increased conservatively above rated kilovolt-amperes, as given in Table 32.015(*e*). On the basis used in this guide for calculating loss of life, life expectancy will be approximately the same as if it had been operated at rated kilovolt-amperes during that period.

TABLE 32.015(*d*)
Loading on Basis of Load Factor

Type of Cooling	Increase in Percent of Rated Kva	Maximum Percent Increase*
Self-Cooled	0.5	25
Water-Cooled	0.5	25
Forced-Air-Cooled	0.4	20
Forced-Oil-Cooled	0.4	20

* Corresponds to 50 percent load factor.

TABLE 32.015(*e*)
Daily Overloads to Give Normal Life Expectancy

Time, Hours	Times Rated Kilovolt-Amperes								
	Self-Cooled and Water-Cooled Transformers			Forced-Air-Cooled Transformers Rated 133 Percent or Less of Self-Cooled Rating			Forced-Air-Cooled Transformers Rated More than 133 Percent of Self-Cooled Rating and All Forced-Oil-Cooled		
††Initial Load (Percent)	90	70	50	90	70	50	90	70	50
½	1.59	1.77	1.89	1.45	1.58	1.68	1.36	1.47	1.50
1	1.40	1.54	1.60	1.31	1.38	1.50	1.24	1.31	1.34
2	1.24	1.33	1.37	1.19	1.23	1.26	1.14	1.18	1.21
4	1.12	1.17	1.19	1.11	1.13	1.15	1.09	1.10	1.10
8	1.06	1.08	1.08	1.06	1.07	1.07	1.05	1.06	1.06

†† Percentages fix the load which is assumed to exist before the short-time load is applied. Use either average load for two hours previous to load above rating or average load for 24 hours (less overload period), whichever is greater.

Ambient temperature assumed for this table is 30 C for air and 25 C for water.

As the loads may be applied once every 24 hours, and as there is some evidence that the rate of insulation deterioration at about 100 C doubles with less than 8 C increase in insulation temperature, the values have been based on 4 C rather than on 8 C.

f. Effect of Various Factors Existing at One Time. When two or more of the following factors affecting loading for normal life expectancy exist at one time, the effects are cumulative and the increase in loads due to each may be added to secure the maximum suggested load (each increase must be based on rated kilovolt-amperes):

(1) Loading on basis of test temperature rise.

(2) Loading on basis of ambient temperature.

(3) Either loading on basis of load factor or loading on basis of short-time overloads. Do not use both.

CHAPTER XXIII

NEW TRANSFORMERS OR OLD?

When does it pay to throw away old transformers and replace them with new ones? Obviously, no general answer can be given because many factors are involved which differ with conditions. Certain principles can be applied, however, which will lead to the right answer.

To arrive at these principles it is necessary to consider the items of cost in operating a transformer. These items include interest, taxes, depreciation, iron loss, magnetizing current, copper loss, and regulation.

Interest and taxes are evident items in the cost of operation. Besides these, an annual amount must be charged against the transformer for depreciation so that its value will be written off during its life. Interest, taxes, and depreciation are often grouped together as *investment charges* and may run annually from 11 to 16 per cent of the cost of the transformer.

Iron loss is the energy required to magnetize and demagnetize the core. Actual power must be supplied from the line as long as the transformer is excited, whether it is delivering power or not. Recognizing this fact designers have done much to reduce iron loss, as is shown in the table on page 215, which gives the iron and copper losses for high-grade 2,300-volt distribution transformers. The improvement has resulted from better designs and better core material.

Magnetizing current is the wattless component of the current required to magnetize the iron. In itself, it does not represent a power loss, but it adds to the current in the primary winding of the transformer and in the lines and generator and thus increases the copper loss somewhat. Since the magnetizing current is out of phase with the load current, its addition to the copper loss is small.

Copper loss, or *load loss*, *i.e.*, the I^2R loss in the windings plus the stray loss, varies as the square of the load current.

Regulation is defined as the percentage rise in voltage when full load is thrown off the transformer, rated voltage being maintained on the primary. It depends on the resistance and reactance of the transformer, but the higher the power factor of the load the less the effect of reactance. With loads of unity power factor the regulation is nearly equal to the resistance drop; *i.e.*, the percentage of regulation nearly equals the percentage of copper loss. Regulation is often disregarded as an item in the cost of operating a transformer. It has, however, a definite effect as may be seen by considering a distribution system. Voltage regulators are set to maintain normal voltage at certain points in the primary mains. Voltage drop in the transformers, therefore, means decreased voltage delivered to the load, which may cause loss of production to the power user and loss of revenue to the power company where power is purchased.

LOSSES IN WESTINGHOUSE 2300- TO 230–115 VOLT DISTRIBUTION TRANSFORMERS FROM 1907 TO 1948

Date	Up to 1907				1908–1916		1917–1926		1927–1929		1930–1940		1941–1944		1945–1948	
Type	*OD*[*]		*C*[†]		*S*		*S*		*S*		*S*		*S*		*S*	
Kva	Fe[‡] loss	Cu[§] loss	Fe loss	Cu loss	Fe loss	Cu loss	Fe loss	Cu loss	Fe loss	Cu loss	Fe loss	Cu loss	Fe loss	Cu loss	Fe loss	Cu loss
1.5	48	60	33	43	26	37	21	51	20	50	20	46	23	37	22	37
3	73	98	47	67	38	65	33	63	30	76	27	71	30	58	30	58
5	92	151	62	102	43	118	45	83	39	104	37	104	41	93	40	93
7.5	137	185	85	149	60	151	60	107	54	133	50	142	53	129	50	129
10	159	237	100	186	70	186	70	160	67	173	59	183	65	165	62	165
15	195	362	139	278	96	261	106	177	90	260	80	253	88	230	83	230
25	270	460	185	452	134	442	140	310	128	380	120	376	120	376	114	376
37.5	. .		263	680	180	535	200	400	184	480	155	495	154	495	146	495
50		.	300	740	236	749	250	500	235	585	190	605	190	605	186	605

[*] The cores of type *OD* transformers are of nonsilicon steel which is subject to aging, and their iron loss may increase from 10 to 30 per cent after about a year's operation.

[†] Type *C* transformers and type *S* transformers built since 1909 have nonaging silicon-steel cores.

[‡] Fe = iron.

[§] Cu = copper.

The factors previously mentioned can be given pretty definite values. Other characteristics cannot, although they affect the desirability of the transformer, and they may have different values, depending on whether the transformer is on the lines of a power company or in an industrial plant. The weight and size, for instance, of distribution transformers for a given output have shown a steady decrease. At the same time appearance has been improved. Insulation strength and permanence are much better in modern transformers than in the older types, and the probable life of the transformer is therefore longer. Some modern transformers are provided with auxiliary devices which almost completely protect the transformer from damage by lightning and thus ensure continuity of service.

With these factors in mind two questions may be raised: (1) If a damaged transformer has been removed from service, should it be repaired or replaced with a new transformer? (2) Should an old transformer now in service be removed and replaced?

One large operating company has answered the first question by assuming that repairs will prolong the life of the transformer five years and that the difference in cost of operating the old transformer and the new lies in the fixed charge on the increased investment and the cost of iron losses. The economical cost of repairs, then, would be anything less than five times the difference between the fixed cost plus iron-loss cost on the new transformer and the iron-loss cost for the old transformer. This neglects the effect of copper loss and regulation, which may be considerable in some cases.

For example, a 25-kva transformer built before 1907 has been taken out of service for repair. Assume that a new 25-kva transformer will cost \$230. It is desired to amortize the cost of this transformer at 5 per cent per year, and the interest rate on the investment is 5 per cent. Then the fixed charges will be $230 \times 0.10 = \$23$. The iron loss in the new transformer as given in the table is 114 watts. Assuming the transformer to be on the line continuously, the iron loss is

$$(114 \times 8760) \div 1{,}000 = 998.6 \text{ kw-hr, say, } 1{,}000 \text{ kw-hr}$$

At 1 cent per kilowatt-hour the iron loss cost is

$$1{,}000 \times 0.01 = \$10$$

and the total charge is $\$23 + \$10 = \$33$ per year.

In the old transformer the iron loss was 270 watts. If we assume that it has increased 20 per cent because of aging of the core iron, then the present iron loss is $1.20 \times 270 = 324$ watts. In one year of continuous operation this loss amounts to

$$(324 \times 8{,}760) \div 1{,}000 = 2{,}838 \text{ kw-hr}$$

At 1 cent per kilowatt-hour this power is worth

$$2{,}838 \times 0.01 = \$28.38$$

This is $4.62 less than the annual cost of the new transformer, and therefore, according to this method of accounting, repairs up to $4.62 × 5 = $23.10 would be justified. If more than this were required, it would be profitable, according to this rule, to junk the old transformer and install a new one. Many engineers would be inclined to take copper loss and regulation also into account. This would make the comparison more favorable to the new transformer.

To answer the question, "Should a transformer now in service be replaced?" consider the 25-kva transformer in the previous example. There are several ways of considering this problem, but the simplest is to determine how quickly the savings in iron loss and copper loss will pay for the new transformer. If this period is satisfactory, the other considerations can generally be neglected. In the new transformer the iron loss is 114 watts, and in the old transformer it is 324 watts, or a difference of 210 watts in favor of the new transformer. The full-load copper losses of the two transformers are 376 and 460 watts, respectively, or a difference of 84 watts in favor of the new transformer.

Assume that the transformer operates under conditions to make the average copper loss equal to 50 per cent of the full-load copper loss. Then the saving in copper loss is 84 × 0.5 = 42 watts. The total saving, then, is 210 + 42 = 252 watts, or

$$(252 \times 8{,}760) \div 1{,}000 = 2{,}208 \text{ kw-hr per year}$$

in favor of the new transformer. At 1 cent per kilowatt-hour this would amount to a saving of $22.08 per year to pay interest on the investment in the new transformer and to amortize its cost. If the new transformer cost $230 and the interest rate is 5 per cent, the annual saving will pay for the transformer in something less than fifteen years, allowing interest each year on the unamortized part of the cost. When other factors, such as better regulation and improved reliability, are considered, it may be decided that the new transformer will be a good investment.

In the calculation no allowance has been made for the cost of installing the new transformer, and it has been assumed that the junk value of the old transformer will about equal this cost. No account has been taken of taxes and insurance, but taxes should be about the same on the two, and insurance should be considerably less on the new transformer than on the old.

The figures used above will differ for various plants and according to the judgment of various engineers, but the general method can be applied

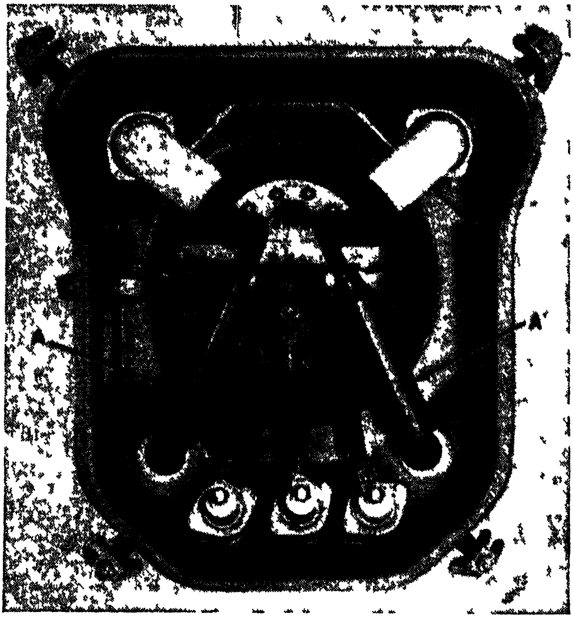


FIG 201 Looking into the top of a distribution transformer equipped with deion gaps

A new transformer should operate for many years, under normal conditions, with little or no cost for repairs other than painting or minor repairs to external wiring such as would be required by the old transformer. Internally the new transformer will probably require no attention, but the old transformer will very likely need to be taken out of service for cleaning and renewing the oil The possibility that the old transformer will fail in service and require replacement or extensive repair is many times stronger than for the new transformer.

Modern transformers are smaller, lighter, and better in appearance than old types, but their outstanding advantage, outweighing perhaps even the decreased losses, is better insulation and protective features designed to ensure continuity of service. Distribution transformers can be had with protective gaps between the leads, tank, and ground so that any surge will be discharged to ground without puncturing the insulation. The gaps embody the deionizing principle, so that the power arc which tends to follow the surge is extinguished before the fuse is blown. This conquers two foes of good service, punctured insulation and blown fuses, and it is a strong reason for replacing old transformers. Figure 201 is a view looking into the top of a distribution transformer and shows deion gaps at *A*.

The answer to the question of replacement may be purely economic, based on losses, or this answer may be modified by the need for improved reliability.

CHAPTER XXIV

TRANSFORMER CALCULATIONS

In this chapter several problems will be worked out to show the derivation of formulas which have been given in other chapters and to illustrate a method which can be applied to the solution of many alternating-current problems. The solutions can be carried out graphically by the well-known method of drawing a diagram to scale and measuring the required lines, or they can be carried out analytically from the known relations of lines and angles. Even in the analytical solution, however, a vector diagram is helpful in visualizing the problem.

In the examples which follow it is assumed that the power factor of the load is 100 per cent. This does not imply any lack of generality in the results, because any other power factor would merely rotate all the current vectors by the same amount with respect to the voltage vectors. It would not affect the relations between currents or the relations between voltages.

In the diagrams, voltages and currents are generally designated by E and I with double subscripts. These subscript letters correspond to the letters on the diagram of connections and indicate the direction through the circuit of the quantity shown; thus I_{AB} means current flowing from A to B and is opposite in direction to the current I_{BA}.

Example 1. Transformers in Scott Connection. A balanced two-phase load of 100 kva is to be supplied from a 100-volt three-phase line through transformers in Scott connection. Find the currents and voltages in the windings and the size of parts required.

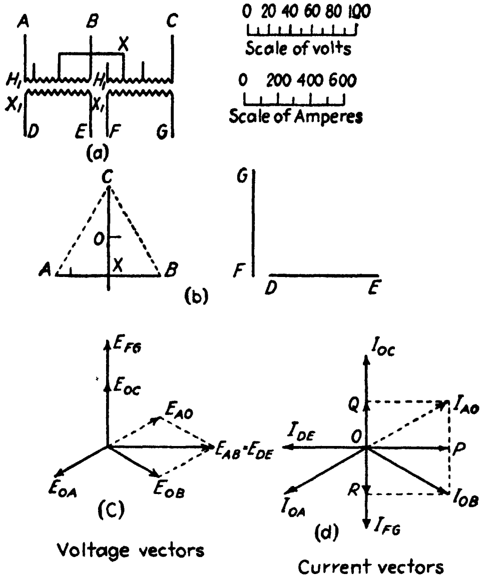
Solution: Figure 202*a* shows the connection of the transformers. The current in the two-phase lines D, E, F, G will be

$$I_2 = \frac{100 \times 1{,}000}{100 \times 2} = 500 \text{ amperes}$$

and the current in the three-phase lines A, B, C will be

$$I_3 = \frac{100 \times 1{,}000}{100 \times \sqrt{3}} = 577.4 \text{ amperes}$$

Graphic Solution: In Fig. 202*b*, lay off points A, B, and C to form an equilateral triangle to scale, 100 volts on each side. Draw the line AB, which will represent the primary voltage of the main transformer. Perpendicular to AB draw a line through C. The intersection of this line with AB at the point X gives the voltage applied to the teaser and consequently the location of the tap on the teaser winding. Scaling the diagram, $CX = 86.6$ volts, and $AX = XB = 50$ volts. In order to make the two transformers alike it is customary to put a tap X also in the main transformer at 86.6 per cent of the winding and to extend the teaser winding beyond the point X so that it will have the same number of turns as the main transformer winding. It is also customary to put a middle tap in the teaser. This gives two unused taps but makes the two transformers interchangeable. The point O in Fig. 202*b* does not represent a tap. It is the neutral point of the triangle ABC and is used as a reference point in the vector diagrams. The line FG parallel to XC and equal to 100 volts represents one of the two-phase voltages, and DE, parallel to AB, represents the other



Voltage vectors

Current vectors

FIG. 202. Transformers in Scott connection.

In Fig. 202*c* the voltage vectors are drawn to show their phase relations. The voltage from neutral to each of the three-phase lines is shown by the lines E_{OA}, E_{OB}, and E_{OC}, respectively. The voltage from X to C will obviously be in phase with E_{OC}, and the secondary voltage E_{FG} will be in the same phase, since the polarity marks (H_1 and X_1, Fig. 202*a*) show that the point G has the same relative polarity as C. In the main transformer the voltage from A to B will be the vector sum of E_{AO} and E_{OB}, which is E_{AB} as shown in the diagram, and the secondary voltage E_{DE} will be represented by the same line, since the polarity marks show that A has the same relative polarity as D.

In determining how to lay off the current vectors an analogy may be helpful. Consider a motor generator set. The motor takes energy from the line, and the current inside the motor flows from the positive terminal to the negative terminal, or in the same direction as the voltage. The generator delivers energy to the line, and the current inside the generator flows from the negative terminal to the positive terminal, or in a direction opposite to the voltage. In the same way a transformer primary winding takes energy from the line and the current is in the same direction as the voltage, but the secondary winding delivers energy to the line, and the current inside the winding is opposite in direction to the voltage. Primary currents, therefore, will be shown in the same direction as the voltages which produce them, and secondary currents in the opposite direction. This distinction is specially important in problems involving autotransformers.

Now referring to Fig. 202*d*, the three-phase currents I_{OA}, I_{OB}, and I_{OC} are laid off equal to 577.4 amperes and parallel, respectively, to E_{OA}, E_{OB}, and E_{OC} and in the same direction. Also the two-phase currents I_{DE} and I_{FG} are laid off equal to 500 amperes and parallel respectively to E_{DE} and E_{FG}, but in opposite directions.

Since voltage is proportional to turns, we may say that in the primary winding of the teaser we have I_{OC} in 86.6 turns and in the secondary we have I_{FG} in 100 turns.

$$577.4 \times 86.6 = 500 \times 100$$

and therefore the ampere turns in the primary winding of the teaser are equal and opposite to those in the secondary winding, which is the necessary condition.

In the primary winding of the main transformer, I_{AO} flows from

A to X, and I_{OB} from X to B. Each of these currents may be resolved into two components. I_{AO} has a horizontal component OP and a vertical component OQ, and I_{OB} has a horizontal component OP and a vertical component OR. Now OQ flowing from A to X evidently neutralizes OR flowing from X to B as far as net ampere turns are concerned. This leaves effective OP flowing from A to B, and OP scales 500 amperes. In the main transformer, therefore,

$$500 \times 100 = 500 \times 100$$

or the primary ampere turns balance the secondary ampere turns.

Analytical Solution: In Fig. 202*b*,

$$AB = BC = CA = 100 \text{ volts}$$

and

$$\text{angle } BCX = 30 \text{ degrees}$$

therefore $CX = 100 \cos 30 = 100 \times 0.866 = 86.6$ volts, as before.

In Fig. 202*d*, I_{AO} is 30 degrees above the horizontal and I_{OB} is 30 degrees below the horizontal. Therefore the horizontal component of each is

$$OP = 577.4 \cos 30 = 577.4 \times 0.866 = 500 \text{ amperes}$$

and the vertical components are

$$OQ = OR = 577.4 \sin 30 = 577.4 \times 0.5 = 288.7 \text{ amperes}$$

Size of Parts. The primary winding of each transformer must have a conductor large enough to carry 577.4 amperes and turns enough for 100 volts. The secondary winding must carry 500 amperes at 100 volts. Therefore for each transformer the

$$\text{Size of parts} = \frac{577.4 \times 100 + 500 \times 100}{2 \times 1{,}000} = 53.87 \text{ kva}$$

Example 2. Transformers in Taylor Connection. A balanced two-phase load of 100 kva at 100 volts is to be supplied from a 100-volt three-phase line through transformers using the Taylor connection. Find the currents and voltages and the size of parts required.

Solution: The connection is shown in Fig. 203*a*. The three-phase primary leads are A, B, and C, and the two-phase secondary leads are D, E and F, G. The current in each of the primary lines will be 577.4 amperes, as in Example 1, and the current in the primary winding of each transformer will be

$$577.4 \div \sqrt{3} = 333.3 \text{ amperes}$$

The current in each of the two-phase lines will be 500 amperes.

Graphic Solution: To represent the primary voltages draw the equilateral triangle ABC (Fig. 203*b*) with each side equal to 100 volts. For the secondary voltages (Fig. 203*c*) draw the line Ga parallel to CA and the line Gb parallel to CB, and bisect the angle aGb by a line GF. Lay off $GF = GD = GE = 100$ volts, and through the point F draw a line ab parallel to DE. Scaling the diagram, it is found that D and E are taps 100 volts from G and that the total secondary voltages ab, bG and Ga are each 115.5 volts.

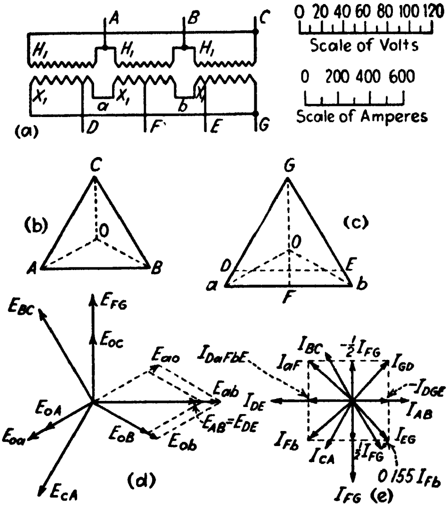


FIG. 203. Transformers in Taylor connection.

Figure 203*d* shows the relative phase position of the two-phase and the three-phase voltages.

The current vectors are shown in Fig. 203*e*. I_{AB}, I_{BC}, and I_{CA}, each equal to 333.3 amperes, are parallel, respectively, to E_{AB},

E_{BC}, and E_{CA} (Fig. 203*d*). The two-phase currents I_{DE} and I_{FG}, each equal to 500 amperes, are opposite, respectively, to E_{DE} and E_{FG}.

The current I_{FG} has two paths from F to G, *FaDG* and *FbEG*, and from the symmetry of the circuit it is evident that the current will divide equally between these two paths. Similarly the current I_{DE} has two paths, *DGE* and *DaFbE*. We shall assume that the current divides in inverse proportion to the number of turns through which it must flow and then check to find if this assumption gives balanced ampere turns in each transformer.

The turns in circuit *DGE* are proportional to the voltage, or

$$100 + 100 = 200$$

and the turns in circuit *DaFbE* are proportional to

$$15.5 + 115.5 + 15.5 = 146.5$$

Therefore

$$I_{DGE} = 500 \times \frac{146.5}{200 + 146.5} = 211.4 \text{ amperes}$$

and

$$I_{DaFbE} = 500 \times \frac{200}{200 + 146.5} = 288.6 \text{ amperes}$$

Both these currents, of course, will be in phase with I_{DE}, of which they are parts.

Then the current flowing in the part of the winding from a to F is

$$I_{aF} = I_{DaFbE} + (-\tfrac{1}{2}I_{FG}) = 381.8 \text{ amperes}$$

as shown in Fig. 203*c*, and the current from F to b is

$$I_{Fb} = I_{DaFbE} + \tfrac{1}{2}I_{FG} = 381.8 \text{ amperes}$$

The vertical component of I_{aF} in one half of the secondary winding *ab* is equal and opposite to the vertical component of I_{Fb} in the other half of the same winding, and the net ampere turns of these two components are zero. This leaves, in effect, the current I_{DaFbE}, flowing through the whole secondary winding *ab*, opposite in phase to the primary current I_{AB} in the same transformer.

$$100 \times 333.3 = 115.5 \times 288.6$$

and therefore the primary ampere turns are equal and opposite to the secondary ampere turns in transformer *AB*.

In the winding *bG* the current from *b* to *E* is evidently the same as I_{Fb}, since current does not enter or leave the circuit at *b*. The current from *E* to *G* is

$$I_{EG} = \tfrac{1}{2}I_{FG} + (-I_{DGE}) = 327.5 \text{ amperes}$$

as shown in the figure. And I_{EG} flowing in 100 per cent turns plus I_{Fb} in 15.5 per cent turns gives a resultant equal and opposite to the primary current I_{BC} in 100 per cent turns. Thus the ampere turns in the transformer *BC* are balanced.

Similarly, the current in the winding *GD* is

$$I_{GD} = -I_{DGE} + (-\tfrac{1}{2}I_{FG}) = 327.5 \text{ amperes}$$

and

$$I_{Da} = I_{aF} = 381.8 \text{ amperes}$$

and the total ampere turns in the secondary winding of transformer *CA* are equal and opposite to those in the primary winding.

Analytical Solution: In Fig. 203*c*, $DE = FG = 100$ volts, and the angle *FGb* is 30 degrees. Therefore

$$Gb = \frac{100}{\cos 30} = \frac{100}{0.866} = 115.5 \text{ volts}$$

In Fig. 203*c* I_{aF} is the vector sum of I_{DaFbE} and $(-\tfrac{1}{2}I_{FG})$. Since these two components are at right angles to each other,

$$I_{aF} = \sqrt{(I_{DaFbE})^2 + (-\tfrac{1}{2}I_{FG})^2} = \sqrt{(288.6)^2 + (-250)^2}$$
$$= 381.8 \text{ amperes}$$

This is the same figure as was found above, and the part available to balance the primary ampere turns is 288.6 amperes, as before.

In the transformer *BC*, the current I_{EG} is composed of a horizontal component $(-I_{DGE}) = 211.4$ amperes and a vertical component $\tfrac{1}{2}I_{FG} = 250$ amperes. Its numerical value will then be

$$I_{EG} = \sqrt{(-I_{DGE})^2 + (\tfrac{1}{2}I_{FG})^2} = \sqrt{(-211.4)^2 + (250)^2}$$
$$= 327.5 \text{ amperes}$$

The current I_{Fb}, which flows from *b* to *E* in this transformer, has a horizontal component $I_{DaFbE} = 288.6$ amperes and a vertical component $\frac{1}{2}I_{FG} = 250$ amperes. I_{EG} flows in 100 per cent turns and I_{Fb} in 15.5 per cent turns. If we assume that vectors to the right or upward are positive and vectors to the left or downward are negative, we may write*

Current	Horizontal component	Vertical component
100 per cent I_{EG}	211.4	−250
15.5 per cent I_{Fb}	− 44.7	− 38.8
Resultant	166.7	−288.8

The numerical value of this resultant is

$$\sqrt{(166.7)^2 + (-288.8)^2} = 333.3 \text{ amperes}$$

and its angle from the vertical is the angle whose tangent is $166.7 \div 288.8 = 0.577$. This is the tangent of 30 degrees to the right of the vertical. Since the primary ampere turns are 100 per cent turns times 333.3 amperes 30 degrees to the left of the vertical, as shown in the figure, the total ampere turns of this transformer are balanced.

Size of Parts. Collecting the figures which have been obtained,

Winding part	Volts	Amperes
A to *B*	100.0	333.3
B to *C*	100.0	333.3
C to *A*	100.0	333.3
a to *b*	115.5	381.8
b to *E*	15.5	381.8
E to *G*	100.0	327.5
G to *D*	100.0	327.5
D to *a*	15.5	381.8

---

* In the usual complex quantity notation this would be written

100 per cent I_{EG} $= 211.4 - j250$
15.5 per cent $I_{Fb} = 0.155(-288.6 - j250) = -44.7 - j38.8$

Resultant $= 166.7 - j288.8$
$= 333.3$ amperes

The transformer *AB*, therefore, requires parts

$$\frac{100 \times 333.3 + 115.5 \times 381.8}{2 \times 1{,}000} = 37.72 \text{ kva}$$

Transformer *BC* requires parts

$$\frac{100 \times 333.3 + 15.5 \times 381.8 + 100 \times 327.5}{2 \times 1{,}000} = 36 \text{ kva}$$

And transformer *CA* requires parts the same as transformer *BC*, or 36 kva.

Example 3. Autotransformers in Scott Connection. A balanced two-phase load of 100 kva at 100 volts is to be supplied from a 200-volt three-phase line, using autotransformers. Find the currents, voltages, and size of parts.

Solution: The connection is shown in Fig. 204*a*. *A*, *B*, and *C* are the three-phase leads, and *D*, *E* and *F*, *G* are the two-phase leads. The three-phase current per lead will be

$$\frac{100 \times 1{,}000}{200 \times \sqrt{3}} = 288.7 \text{ amperes}$$

and the two-phase current per lead is

$$\frac{100 \times 1{,}000}{100 \times 2} = 500 \text{ amperes}$$

Graphic Solution: For the voltages, lay out an equilateral triangle, *ABC* (Fig. 204*b*) with 200 volts on each side, and bisect the angle at *C* by a line perpendicular to the base. This line *CF* scales 173.2 volts and gives the total voltage on the teaser winding. The two-phase voltage *DE* is taken from half the turns of the main autotransformer, and the voltage *FG*, equal to *DE*, is taken from the teaser and is therefore at right angles to *DE*. The point *O* is a reference point at the neutral of the three-phase circuit.

Figure 204*c* shows the phase relations of the voltages, and Fig. 204*d* shows the current vectors. I_{OA}, I_{OB}, and I_{OC} are each equal to 288.7 amperes and parallel, respectively, to E_{OA}, E_{OB}, and E_{OC} (Fig. 204*c*). The two-phase currents I_{DE} and I_{FG} are each equal to 500 amperes and opposite in phase to E_{DE} and E_{FG}, respectively.

In the main autotransformer the current from *A* to *D* is the current I_{AO}. The current from *D* to *F* is the vector sum of I_{AO}

and I_{DB} and is shown in Fig. 204*d* as I_{DF}. It measures the same as I_{AO}, or 288.7 amperes. Similarly, the current from F to E is I_{DB} plus I_{OB}, shown in the diagram as I_{FB}, and measures 288.7 amperes. And the current from E to B is I_{OB}. It is thus seen that the current is numerically the same in each of the four equal parts of the winding AB, and from the symmetry of the diagram it is evident that the net ampere turns on the core from these four parts are zero. This is the necessary condition.

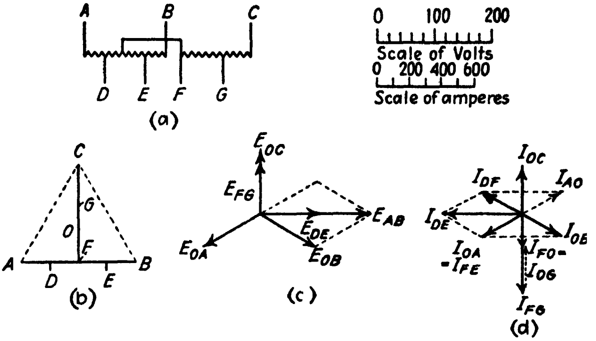


FIG. 204. Autotransformers in Scott connection.

In the teaser, I_{OC} flows from G to C. The current from F to G is the resultant of I_{OC} and I_{FG}, and since these two currents are exactly opposite in phase, their resultant will be the numerical difference, as shown in Fig. 204*d* at $I_{FO} = I_{OG}$.

$$100 \times (500 - 288.7) = (173.2 - 100) \times 288.7$$

and thus the ampere turns on the teaser core are balanced.

Analytical Solution: The angle FCB in Fig. 204*b* is 30 degrees, and therefore $CF = CB \cos 30 = 200 \times 0.866 = 173.2$ volts across the teaser.

Referring to Fig. 204*d*, I_{AO} is 30 degrees above the horizontal. Its horizontal projection, therefore, is

$$288.7 \cos 30 = 288.7 \times 0.866 = 250 \text{ amperes}$$

which is half of I_{DE}. The resultant current I_{DF}, then, must be 30 degrees above the horizontal and numerically equal to I_{AO}, or 288.7 amperes.

Size of Parts. For the main autotransformer the size of parts is

$$\frac{50 \times 288.7 \times 4}{2 \times 1{,}000} = 28.87 \text{ kva}$$

and for the teaser the size of parts is

$$\frac{100 \times (500 - 288.7) + (173.2 - 100) \times 288.7}{2 \times 1{,}000} = 21.13 \text{ kva}$$

Example 4. Autotransformers in Modified Scott Connection. A balanced two-phase load of 100 kva at 200 volts is to be supplied from a 100-volt three-phase line, using autotransformers. The two phases on the two-phase side are to have a common neutral. Find currents, voltages, and size of parts.

Solution: The connection is shown in Fig. 205*a*. The middle points of the two autotransformers are connected together, and taps A, B, and C are located so that the three-phase voltage can be applied. The three-phase current in each line is

$$\frac{100 \times 1{,}000}{100 \times \sqrt{3}} = 577.4 \text{ amperes}$$

and the two-phase current per line is

$$\frac{100 \times 1{,}000}{200 \times 2} = 250 \text{ amperes}$$

Graphic Solution: Draw two lines at right angles to each other, each 200 volts long, as in Fig. 205*b*, intersecting at their middle points. Lay off A halfway between D and H and lay off B halfway between H and E. On AB as a base construct an equilateral triangle ABC. Then the distance HC will scale 86.6 volts. O is the neutral point of the triangle and is a reference point.

The phase relations of the various voltages are shown in Fig. 205*c*, and Fig. 205*d* shows the current vectors. I_{OA}, I_{OB}, and I_{OC} are parallel, respectively, to E_{OA}, E_{OB}, and E_{OC}, and each is equal to 577.4 amperes. I_{DE} and I_{FG} are laid off opposite to E_{DE} and E_{FG}, Fig. 205*c*, and each is equal to 250 amperes.

The two-phase current, 250 amperes, must flow in the parts of the winding from D to A, from B to E, from F to H, and from C to G. The part of the winding from A to H carries I_{AO} plus I_{DE}. This vector addition is shown in Fig. 205*d* and gives I_{AH}, which scales 381.9 amperes. The part of the winding from H to B carries I_{OB} plus I_{DE}, which gives I_{HB} as shown in the figure and is 381.9 amperes. The part of the winding from H to C carries I_{OC} plus I_{FG}. These two currents are exactly opposite in phase, as shown in the diagram, and their resultant is the numerical difference, or $577.4 - 250 = 327.4$ amperes $= I_{HC}$.

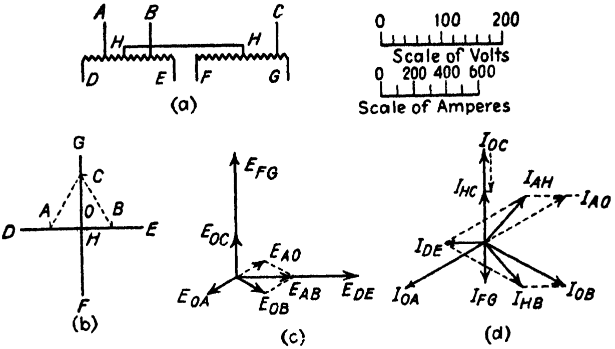


FIG. 205. Autotransformers, three-phase to two-phase, five-wire.

Analytical Solution: The currents I_{AO} and I_{OB} (Fig. 205*d*) are each 30 degrees from the horizontal and equal to 577.4 amperes. The horizontal component of each, then, will be

$$577.4 \cos 30 = 577.4 \times 0.866 = 500 \text{ amperes}$$

and the vertical components will be

$$577.4 \sin 30 = 577.4 \times 0.5 = 288.7$$

The current I_{DE} has no vertical component. To add them, therefore, we may write*

Current	Horizontal component	Vertical component
Current I_{AO}	500	288.7
Current I_{DE}	−250	0.0
Resultant current I_{AH}	250	288.7

---

*See footnote on page 232.

Numerically, then, I_{AH} is $\sqrt{(250)^2 + (288)^2} = 381.9$ amperes.

In the main autotransformer the current I_{DE} flowing from D to A and from B to E (50 + 50 volts) is equal and opposite to the horizontal components of I_{AH} and I_{HB} flowing in (50 + 50) volts. Also the vertical components of these two currents are equal and opposite. The total ampere turns on the core of the main autotransformer are therefore zero.

In the teaser, the current $I_{HC} = 327.4$ amperes and flows in turns corresponding to 86.6 volts, and the current

$$I_{FG} = 250 \text{ amperes}$$

in turns corresponding to 100 + 13.4 = 113.4 volts. Thus the ampere turns on the teaser are balanced.

Size of Parts. For the main autotransformer the size of parts is

$$\frac{2 \times 50 \times 250 + 2 \times 50 \times 381.9}{2 \times 1{,}000} = 31.5 \text{ kva}$$

and for the teaser the size of parts is

$$\frac{113.4 \times 250 + 86.6 \times 327.4}{2 \times 1000} = 56.7 \text{ kva}$$

The essentials of this method are representing the known currents and voltages by vectors of the proper size and phase relation and then combining these vectors according to the conditions of the problem to find the unknown quantities.

---

*In the notation of complex quantities this would be written

$$\begin{array}{llll}
I_{AO} = & 500 + j288.7 & I_{OB} = & 500 - j288.7 \\
I_{DE} = & -250 & I_{DE} = & -250 \\
\hline
I_{AH} = & 250 + j288.7 & I_{HB} = & 250 - j288.7 \\
 = & \sqrt{(250)^2 + (288.7)^2} & = & \sqrt{(250)^2 + (288.7)^2} \\
 = & 381.9 \text{ amperes} & = & 381.9 \text{ amperes}
\end{array}$$

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